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FOREWORD

Dear colleagues and friends,

Welcome to the 23rd International Logistics and Supply Chain Congress (LMSCM 2025).

Artificial Intelligence is the fastest-adopted technology in human history. Each day brings new tools, new opportunities, and new concerns. Generative AI, in particular, is transforming our world at an unprecedented pace. Today, before discussing almost any topic—even a medical report—we often say, "Let's ask ChatGPT." This simple phrase reflects a profound shift not only in how we process text or images, but in how we think, learn, and make decisions. Yet saying "we use AI" is fundamentally different from saying "we create value with AI."

What makes this moment unique is not only the speed of technological progress, but also the intensity of the surrounding hype. Logistics and supply chain operations stand out as domains where digital solutions and AI-driven innovations can be implemented rapidly and can generate tangible, short-term returns. At the same time, these technologies raise important questions about resilience, sustainability, and the role of human judgment.

This Congress provided an open and inclusive platform for discussion, learning, and collaboration, aiming to rethink and rebalance supply chains in a sustainable and human-centered manner. The presentations delivered during LMSCM 2025 make a valuable contribution to this dialogue. The proceedings bring together inspiring studies on AI-driven logistics, resilient supply networks, and effective human–AI collaboration, reflecting both academic rigor and practical relevance.

I would like to express my sincere gratitude to Prof. Dr. Mehmet Tanyaş, President of LODER and Co-Chair of the Congress, for his leadership and continuous support. I also extend special thanks to our esteemed colleagues from Cranfield University, Prof. Dr. Emel Aktas and Dr. Abhi Ghadghe, for their valuable contributions.

I would like to wholeheartedly thank Istanbul Topkapı University for its strong institutional support, particularly Rector Prof. Dr. Emre Alkin, Chairman Mr. Nihat Kırmızı, and Dean Prof. Dr. Ercan Gegez. My appreciation also goes to Prof. Dr. Ali Halıcı, Prof. Dr. Fazlı Yıldırım, and Dr. Bora Gündüzyeli. I sincerely thank our dedicated assistants: Emre Ömer Zehir, who coordinated the website and review process; Nida Oruç Ünal and Rabia Bilici, who coordinated the publication process; Barış Kutay Değerli and Nagihan Kartal, who provided coordination support across all areas; as well as all administrative staff and our students who contributed to the successful organization of this Congress.

I sincerely hope that the ideas and insights shared in this volume will inspire further research, meaningful dialogue, and practical advancements toward resilient, sustainable, and human-centered supply chains in the era of Generative AI.

Prof. Dr. Batuhan Kocaoğlu
Congress Chair

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TABLE OF CONTENT

BLOCKCHAIN-BASED TRACEABILITY IN ELECTRIC VEHICLE BATTERY SUPPLY CHAINS: STRATEGIC INSIGHTS FROM GLOBAL CASE STUDIES FOR TÜRKİYE

Merve Sezen GÜLER KANDEMİR, Volkan YAVAŞ

Abstract

The rapid global expansion of electric vehicles (EVs) has made it imperative to secure the supply of critical raw materials such as lithium, cobalt, and nickel and ensure their ethical and sustainable traceability. In this context, blockchain technology offers an innovative solution that ensures traceability and data integrity throughout the life cycle of high-risk materials from source to final application.

Through a case study approach, this study analyzes blockchain-based traceability systems implemented by leading firms such as Tesla and CATL. It evaluates the implications of these practices in terms of sustainability, ethical sourcing, and digital transformation. Examples such as the Hyperledger Fabric-based platforms and carbon traceability applications developed in collaboration with Volvo Cars are examined based on publicly available data infrastructure.

It is argued that by integrating blockchain-based traceability systems with PLM and ERP platforms, domestic manufacturers could achieve significant advantages in aligning with international sustainability standards and optimizing their value chains. These findings are particularly relevant for Türkiye’s emerging battery production and energy storage ecosystem.

This study contributes to the evolving academic discourse on digital transformation in battery supply chains by contextualizing global blockchain-based practices for Türkiye. It proposes a national roadmap for the integration of traceability solutions into PLM and ERP systems, offering actionable strategies for alignment with international sustainability standards.

Keywords: Blockchain, Digital Transformation, Electric Vehicles, Supply Chain Traceability, Sustainability.

Related topics: Traceability and Blockchain Applications in Supply Chains, Sustainable and Green Logistics, Digitalization in Logistics and Supply Chains, PLM and ERP Integration in Supply Chains

1. INTRODUCTION

The energy transition has gained significant momentum in today’s world in line with the fight against climate change and sustainability goals. The automotive industry has entered a profound structural transformation in this process. Electric vehicles (EVs), which have become pioneers of this process in line with carbon emission reduction targets, are rapidly increasing their share in the global market, and according to the data of the International Energy Agency [1], a large-scale increase in EV sales is observed. In parallel with this development, the demand for critical raw materials such as lithium, cobalt, and nickel, which are at the heart of battery production, has reached historically unprecedented levels.

This growing demand has also brought to light the often-overlooked dark sides of the battery raw material supply chain. These chains, geographically dispersed, multi-layered, and mostly lacking transparency, also bring serious environmental, social, and governance (ESG) risks. In particular, human rights violations such as unethical working conditions and child labor encountered in cobalt mining in regions like the Democratic Republic of Congo create a significant reputational risk for global brands and raise concerns in the eyes of both consumers and regulatory authorities. With these concerns, companies are forced to adopt and even prove “responsible sourcing” principles.

At this point, supply chain management no longer seeks only to answer the question of “where is the material coming from?”; it is being restructured around much more comprehensive questions such as “is this process transparent enough?”, “is it sustainable?”, and “is it ethical?”.

Within this complex structure, the development of a closed-loop supply chain (CLSC) is of great importance, especially for electric vehicle batteries. The traceability and recovery of battery cells throughout their life cycle have become a strategic necessity in terms of both environmental sustainability and resource security. However, current supply chain management systems generate information silos due to lack of trust among stakeholders and data incompatibilities, and this significantly limits the holistic transparency and traceability of the chain. In addition, legal uncertainties encountered in the supply of raw materials for electric vehicle batteries make it difficult for the chain to operate in an end-to-end auditable and sustainable manner. Indeed, many countries today do not have binding regulations regarding ethical mining practices or verification of the origin of raw materials. In most cases, supply chain transparency relies on voluntary declarations and corporate initiatives. Furthermore, the absence of a sufficiently clarified and binding legal framework at the international level regarding issues such as data ownership, protection of trade secrets, and the degree of information sharing across the chain makes the widespread and secure adoption of blockchain-based systems in supply chain applications difficult.

At this point, blockchain technology comes into play. While traceability in traditional systems is mostly based on fragmented and manual processes, data is stored in silos, leading to both time and trust losses. Blockchain, on the other hand, proposes the opposite model: a decentralized structure that enables every actor in the chain to generate verifiable, immutable, and transparent records at every step.

The fundamental features of blockchain such as decentralization, transparency, immutability, and smart contracts reduce trust issues in the supply chain, increase operational efficiency, and have the potential to improve decision-making processes. At the same time, this technology not only provides economic benefits but also plays a critical role in achieving environmental and social sustainability goals. Enabling all steps to be recorded in an auditable manner throughout the journey of raw materials from the mine to the final product makes it a strategic tool, especially for complex systems such as electric vehicle batteries.

The main purpose of this study is to analyze the role of blockchain technology in the electric vehicle battery supply chain, particularly through the practices of industry leaders such as Tesla and CATL, and to develop applicable and engineering-oriented strategic implications for Türkiye. Within this framework, the analysis presented does not remain limited to simply stating that “blockchain is a good technology”; it also aims to understand the practical barriers encountered in the field and to generate solution proposals specific to Türkiye for these barriers. At the same time, this article is also a product of an effort to transfer my field observations, based on my experiences as a PLM specialist, into an academic framework.

The article is structured in line with these objectives as follows: Section 2 presents the literature review, covering the EV battery supply chain and traceability, the fundamentals of blockchain technology, closed-loop supply chains, and PLM–blockchain integration. Section 3 states the originality of the study. Section 4 describes the methodology. Section 5 analyzes global cases

(Tesla–Re|Source; CATL–Volvo/Circulor; the Re|Source consortium). Section 6 derives strategic implications for Türkiye. Section 7 concludes with key findings and recommendations.

2. LITERATURE REVIEW

In this section, the key concepts forming the basis of the study are addressed systematically. Concepts such as the electric vehicle battery supply chain, traceability, blockchain technology, and Sustainable Supply Chain Management (SSCM) are defined, and their mutual relationships are explained. In addition, how this conceptual structure is approached in the context of Türkiye within the scope of this study is discussed. This framework constitutes the analytical lens of the research and provides a theoretical foundation for all sections from problem definition to solution proposals.

2.1 Electric Vehicle Battery Supply Chain and Traceability

Electric vehicle (EV) batteries are produced within a supply network that is multi-layered and spread across wide geographies. The most fundamental building blocks of this chain are raw materials such as lithium, cobalt, and nickel, which are in high demand and are mostly extracted from limited resources. The supply process is a complex structure that includes mining, refining, cathode/anode production, cell manufacturing, module assembly, and integration steps. This multi-actor structure brings with it a comprehensive need for oversight not only in terms of logistics but also in terms of ethical, environmental, and governance (ESG) responsibilities.

Transparent traceability of the battery supply chain is of critical importance for managing environmental impacts, preventing illegal or unethical practices, and planning recycling processes. However, today many pieces of information in this chain are kept in different systems with different data standards, and sharing among actors often remains limited. This situation has brought to the agenda a high level of need for transparency and verifiability for the entire ecosystem, foremost for automotive manufacturers.

Traceability refers to the uninterrupted and verifiable tracking of the journey of a product or raw material from its source to the end user. In EV battery chains, traceability provides not only compliance with legal obligations but also a significant competitive advantage in terms of substantiating sustainability claims, product liability, and manufacturer reputation.

2.2. Fundamental Principles of Blockchain Technology and the Supply Chain Context

Blockchain is a distributed and immutable digital record system. Fundamentally, it enables the secure retention of data records without the need for any central authority. Each transaction is written into data groups called "blocks," and these blocks are linked to each other in chronological order to form the chain. Since each block in the chain also contains the data of the preceding block, any change to be made in the system affects the entire chain; this inherently renders blockchain immutable and verifiable.

The core features of blockchain technology include the following:

- **Distributed ledger structure:**

  Data is stored not in a single center but on the systems (nodes) of all participants. Thus, even if the entire system collapses, the data is not lost.

- **Transparency:**

  Transactions become observable by all participants.

- **Security:**

Thanks to cryptographic algorithms, the system is highly resistant to external interference.

- **Smart contracts:**

  Transactions that automatically take effect according to predefined rules. They play an important role particularly in managing trigger-based processes in the supply chain.

In the supply chain context, this technology makes it possible to trace, in a transparent and secure manner, the journey of products and raw materials from provenance information to the end user. Especially in multi-actor and globally distributed supply chains, blockchain is a powerful tool in terms of real-time access to information, data integrity, and process verification.

In complex sectors such as EV battery manufacturing, blockchain applications provide the following advantages:

- Verification of product provenance (e.g., mine site, place of manufacture)
- Recording certification and ethical compliance data into the system
- Tracing parts/raw materials retrospectively in recycling loops
- Preventing fraud within the supply process
- Increasing trust among stakeholders through automated records

However, although the technology offers this potential, certain limitations are encountered in practice. In particular, reliance on voluntary data sharing, the inability of different blockchain systems to operate compatibly with one another (interoperability), and the legal uncertainties mentioned above affect the scalability of the system. Therefore, for blockchain technology to be used effectively in supply chains, not only technical but also governance-related and strategic adaptations must be taken into account.

Indeed, the potential of this technology manifests itself in example implementations realized in different sectors, notably food (IBM Food Trust), gemstones (Everledger), and lithium mining (consortia such as Re|Source). In the following sections of this study, how blockchain technology is applied globally with a focus on EV batteries will be discussed in more detail [12] [13] [3].

2.3. Closed-Loop Supply Chain and Sustainability

A closed-loop supply chain (CLSC) is defined as a sustainable supply model that includes recovery and reuse processes, enabling products to regain value after the end of their service life. Unlike the traditional linear supply structure, this model breaks the “take-make-dispose” logic, aiming to re-introduce valuable raw materials into the system and reduce environmental impact. Especially for product groups that contain rare and strategic resources such as lithium-ion batteries, this approach assumes a critical role not only environmentally but also economically and geopolitically.

The extraction of metals such as lithium, cobalt, and nickel used in the production of EV batteries creates supply risks due to limited reserves and entails a significant carbon footprint and social costs. Therefore, the efficient recovery of these materials from end-of-life batteries is indispensable for achieving sustainability goals as well as for ensuring supply security. Moreover, regulatory authorities such as the European Union plan to mandate that such raw materials contain certain proportions of recycled content in the post-2030 period; this turns CLSC structures from a preference into a necessity.

For closed-loop systems to function effectively, products must be digitally traceable starting from the manufacturing stage. Information such as which mine site the materials used to produce a battery cell came from, by which manufacturer it was assembled, and the conditions it was exposed to during use directly affect the recycling route the product will follow when it reaches end of life. However, in today's fragmented data systems, accessing this information is often not possible. At this point, blockchain technology stands out as a powerful tool for establishing the information infrastructure of CLSC structures. Creating a digital identity for each product and tracking the life cycle end-to-end through this identity both facilitates sustainability reporting and accelerates integration into the circular economy.

In this context, designing battery supply chains not only with a production focus but also with a recovery and reuse focus offers strategic advantages for companies in achieving carbon-neutral targets, increasing resource efficiency, and ensuring compliance with regulations.

The REBORN project, supported by the European Union under Horizon Europe, aims to develop solutions that make second-life use technically and commercially feasible in order to strengthen battery circularity. By bringing together components such as modular design, solderless mechanical interconnections, wireless RF communication between cell and BMS, semi-automatic/robotic disassembly, and cybersecure cloud-based data flow, the project seeks to enable the safe, traceable, and cost-effective reuse of second-life battery packs. In addition, the extraction of SoH/aging indicators through physics-based models and artificial intelligence (AI) is targeted; the data architecture is designed with an eye to alignment with the battery-passport initiative taking shape in the EU [10], [16], [17], [18].

In the project, the need for digital identification and trustworthy diagnostics at the cell/module level is supported by the work of the consortium partners. For example, THI highlights a "battery fingerprint" approach for secure authentication and conducts cybersecurity testing [19].

Since, under the EU's new Batteries Regulation (2023/1542), the digital battery passport will become mandatory as of 18 February 2027, the data-integrity and traceability components targeted by REBORN are of critical importance for regulatory compliance [11], [20].

On the other hand, the EU-funded BASE project can be cited as an example of blockchain/DLT-based battery-passport implementations. BASE is developing a Digital Battery Passport (DBP) platform that provides end-to-end traceability and data integrity through distributed-ledger technology (DLT) [21], [22].

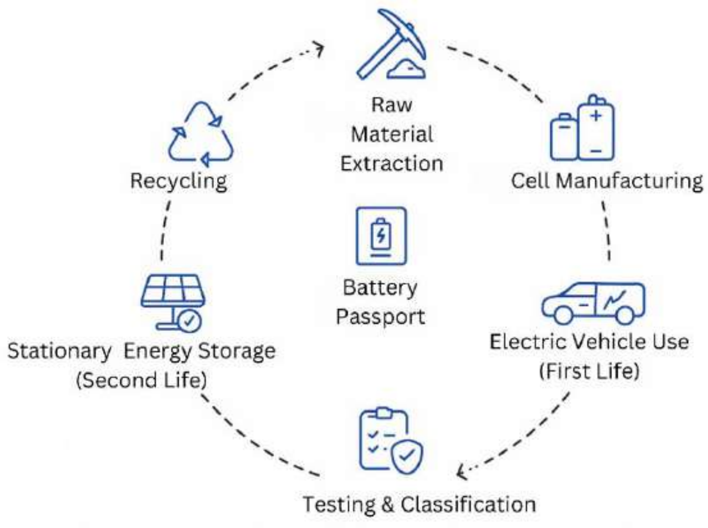

Figure 1. Battery life cycle: Digital traceability across the steps of raw material extraction, cell manufacturing, first life, testing and classification, second-life, and recycling.
(This visual was originally created by the author to support the conceptual framework of the study.)

2.4. PLM and Blockchain Integration

Product Lifecycle Management (PLM) is an integrated approach used to plan, manage, and optimize all processes of a product in digital environments, from ideation to recycling. PLM systems ensure the continuity of engineering data through functions such as Bill of Materials (BOM) management, version control, change management, and configuration tracking. Particularly in multi-component systems, conducting product-related decisions on a central platform in a traceable and repeatable manner carries strategic value in terms of both cost and quality.

In complex and regulated products such as EV battery systems, the data consistency and version tracking provided by PLM systems are indispensable for both manufacturing and recycling planning. However, traditional PLM systems mostly remain limited to in-house data and are inadequate in providing transparency and verifiability across the supply chain. At this point, the integration of blockchain technology with PLM systems creates significant synergy for end-to-end digital traceability at both the corporate and inter-chain levels.

Thanks to blockchain, information such as product structure data (EBOM and MBOM), change records, test reports, or maintenance history contained in PLM systems can be shared not only within internal systems but also with external stakeholders in a transparent, secure, and time-stamped manner. This integration ensures data integrity throughout the product's first life as well as second-life and recycling phases. Blockchain-based battery passports have the potential to enable engineering data produced in PLM systems (e.g., cell configuration, module structure, manufacturing date) to be tracked in an integrated way with field usage and maintenance data. For illustration, the EU-funded REBORN project provides a battery-passport-aligned testbed for end-to-end digital traceability in second-life use cases [10], [19]. From an engineering standpoint, PLM-resident data (EBOM/MBOM, production and test records, maintenance/event history) naturally maps to the mandatory data fields of the EU battery passport (plant & production data, performance/SoH, event history), enabling integration pathways without asserting a specific technology stack [20]. A blockchain/DLT-native route is exemplified by the EU-funded BASE Digital Battery Passport platform [21], [22].

To enable such an integration, PLM systems must be able to communicate with blockchain platforms via open APIs, data formats must be standardized, and authorization levels must be defined. Especially in EV battery manufacturing, PLM and blockchain integration can:

- Prevent supply chain fraud and data manipulation,
- Enable recall processes to be conducted much faster and more target-oriented,
- Facilitate compliance with regulations (e.g., the EU Battery Regulation),
- Allow more efficient dismantling and classification in recycling planning thanks to part-specific data.

From this perspective, a PLM infrastructure supported by blockchain not only digitizes product engineering but also the dimensions of institutional memory management, sustainability reporting, and ethical responsibility; it enables a corporate-level transition to the circular economy of the future.

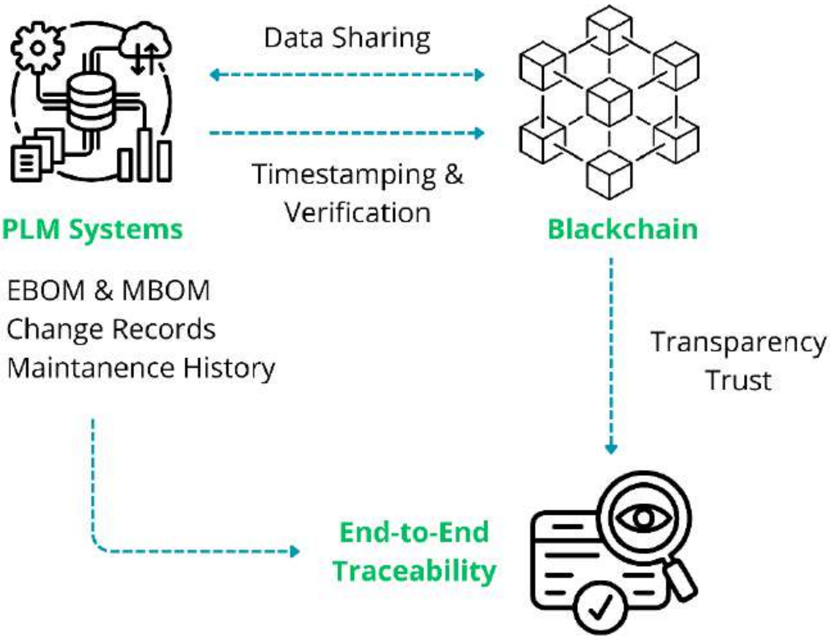

Figure 2. Data sharing and traceability flow between PLM and blockchain systems.
(This visual was originally created by the author.)

3. ORIGINALITY OF THE STUDY

This study consolidates global blockchain traceability cases and positions them within Türkiye's EV-battery context, linking blockchain with PLM and battery-passport requirements. Distinctively, it frames implementation choices (permissioned DLT, interoperability, data-model mapping) as engineering decisions, and derives actionable, Türkiye-specific guidance from real cases.

4. METHODOLOGY

This study is based on a qualitative case analysis method to understand blockchain-based traceability applications in electric vehicle battery supply chains. Methodologically, a systematic literature review and the comparative examination of sectoral examples implemented on a global scale were taken as the basis.

Within the scope of the study, the case examples analysed were the Tesla - Re|Source Consortium, the CATL - Volvo Cars collaboration, and the overall structure of the Re|Source initiative. These examples were selected according to criteria such as sectoral diversity (automotive, battery manufacturing, raw-material mining), scale of implementation (pilot, large-scale deployment), and geographical representation (the United States, China, Europe). The case analyses were structured on the basis of publicly available academic publications, industry reports, and company statements.

In addition, in the selection of examples, how the obligations under the European Union Battery Regulation [11] - such as traceability, carbon-footprint declaration, and responsible sourcing - are met at the implementation level was also taken into account. In this context, how blockchain technology is positioned within the producer–supplier–regulator triangle was analyzed on a case-by-case basis.

During the analyses, the following aspects of each example were evaluated:

- Scope of traceability (e.g., responsible sourcing, carbon footprint, product life cycle),

- The blockchain infrastructure used,
- Actor structure (single firm, consortium, public–private partnership),
- Relationship with regulations,
- Successes and limitations.

The study is explanatory in nature and does not include quantitative data analysis.

5. GLOBAL CASE ANALYSES

In this section, how blockchain applications in the electric vehicle battery supply chain are concretized in the real world is examined. Each case contains noteworthy lessons in both the technology and governance dimensions.

5.1. Tesla and Re|Source (Glencore, CMOC, ERG, and Kryha)

In its 2020 Impact Report, Tesla announced that it had adopted the blockchain-based Re|Source solution for cobalt traceability. Re|Source was established by major DRC-based producers such as Glencore, CMOC, and ERG, and works with Kryha as its technology partner. Pilot studies that began in 2019 start at mine sites in the DRC and extend to battery manufacturing facilities in Europe. Tesla's pilot started in the last quarter of 2021, with full implementation targeted for 2022.

Technology and Model:

The Re|Source platform uses a proprietary blockchain infrastructure developed by Kryha and is designed as a decentralized system that can control data access among industrial stakeholders. Its technical architecture is permissioned rather than public and is configured specifically for sectoral needs. With cryptographically protected, immutable records, Re|Source tracks the true origin of cobalt from the DRC to the battery. On-chain records cover the steps from mining through refining, transportation, supply, and manufacturing. In this way, fraud and misuse can be prevented. Tesla has emphasized that the system is a "universally accessible, scalable, and industry-governed" platform.

Strategic Benefits:

1. **Ethical Governance:** Re|Source offers an effective solution against human-rights violations such as child labor.
2. **Supply Chain Risk Management:** Field-level production tracking is enabled via blockchain records.
3. **Regulatory Readiness:** CO_2 tracking is an important step toward alignment with the EU's forthcoming Battery Regulation and carbon-footprint reporting.
4. **Industry Partnership:** Partnerships with stakeholders such as Kryha, RMI, and Norilsk Nickel increase the system's credibility.

Limitations:

- **Pilot phase:** The pilot that started at the end of 2021 is still not fully scaled.
- **Inter-platform compatibility:** Interoperability with other blockchain solutions (e.g., Circulor, Oracle) is uncertain.
- **Measurement of effectiveness:** The accuracy of field data and the obligations of provider stakeholders are not clear.

- **CO_2 and other raw materials:** The initial phase focused only on cobalt; expansion toward quantitative carbon tracking is planned.

Lessons for Türkiye:

- **Plan interoperability at the design stage.** Define PLM–traceability interfaces early (open APIs; EBOM and test data mapped to chain data objects) and align data models with Regulation (EU) 2023/1542 and the forthcoming Digital Battery Passport.
- **Manage high-risk upstreams.** For sourcing from regions such as the DRC, implement supplier due-diligence and onboarding procedures, and enable low-tech data capture (QR/handheld) to reduce manual-entry risk and improve auditability.
- **Adopt consortium-based governance.** Share costs, standardize data formats and identifiers, and increase credibility with regulators and customers.
- **Mitigate vendor lock-in.** Select permissioned blockchain/DLT solutions that support interoperability, data portability, and evidence export for regulatory audits.

5.2. CATL–Volvo Cars Collaboration & the Circulor Blockchain Platform

In 2019 [5], Volvo Cars partnered with Circulor to ensure traceability of raw-material provenance and carbon footprint across all EV batteries. Within this collaboration, it was aimed to make high-risk minerals such as cobalt and mica traceable from source to final assembly on a blockchain basis (Volvo Cars, Official Statement).

The main battery suppliers, CATL (China) and LG Chem (South Korea), are the direct implementers of this system. The journey of cobalt from the Democratic Republic of the Congo to refineries in China and from there to assembly plants in Europe is recorded via blockchain.

Technology and Model:

Circulor uses a blockchain infrastructure based on Hyperledger Fabric [8] [12]. At every step in the supply chain, data is recorded with cryptographic timestamping. The system can track not only raw materials but also CO_2 emission data. Volvo's XC40 Recharge model, launched in 2020, was the first vehicle integrated into this traceability system [6].

Strategic Benefits:

1. **Carbon-Footprint Traceability:** An infrastructure was established for carbon-footprint reporting that will become mandatory under the EU Battery Regulation.
2. **Proof of Responsible Sourcing:** The origin of raw materials from regions with risks of child labor and environmental violations can be clearly verified.
3. **Competitive Advantage:** Volvo presented traceability as part of its marketing strategy, an element that increased user trust and brand value.
4. **A Forcing Function for Supplier Transparency:** Suppliers not joining the Circulor infrastructure face the risk of being excluded, creating a transparency push across the chain.

Limitations:

- **Data accuracy depends on declarations:** Some on-chain information still relies on manual entry. Unless supported by IoT or machine-based automation, there is a risk of false inputs.

- **Incompatible data systems:** Circulor is not directly integrated with PLM or ERP systems, which can cause breaks in end-to-end digital data flow.
- **Focus on selected raw materials only:** Initially only cobalt, and later mica; other materials (e.g., nickel, manganese) remain outside the system.
- **Not all actors are digitized:** Especially at small-scale mining points in the DRC, basic needs such as digital devices and internet connectivity are still lacking [4].

Lessons for Türkiye:

- **Supply-chain digitalization** must cover the entire chain, not only corporate manufacturers but also lower-tier subcontractors and miners.
- **Carbon-footprint tracking** constitutes preparation for regulations that will soon be mandatory in Türkiye as well; with these systems, manufacturers can differentiate not only in product quality but also in environmental compliance.
- The **PLM–Blockchain - Carbon analytics** triangle provides strategic advantages not only for manufacturing but also for accessing credit financing and attracting ESG investment.

5.3. Re|Source Consortium: A Multi-Actor, Multi-Layered Blockchain Model

Re|Source is a blockchain consortium established to ensure the transparent traceability of cobalt - required for electric vehicle batteries [3] -from its source to final product assembly. It was founded in 2019 by some of the world's leading mining companies, including Glencore, Eurasian Resources Group (ERG), and China Molybdenum (CMOC). Kryha serves as the technological solution partner, and the structure is operated under the Re|Source Foundation.

The main objective is to make it demonstrable that cobalt, especially that extracted from the Democratic Republic of the Congo, is not produced through unethical means such as child labor and environmental violations. It also aims to make sustainability components such as CO_2 footprint and material responsibility traceable (S&P Global, Re|Source website).

Technology and Model:

Re|Source operates with a permissioned blockchain architecture. The platform is custom-developed by Kryha and is decentralized and industry-governed. Data entries are made at every stage; mining, refining, transportation, battery manufacturing, and final assembly. These records are stored in a cryptographically verified, time-stamped, immutable format. Re|Source has included cross-platform blockchain interoperability in its long-term vision; however, it is currently limited.

Actor Structure:

- Some of the world's largest cobalt miners, such as Glencore, CMOC, and ERG, are within this structure.
- Kryha is the blockchain solution partner [9].
- Manufacturers such as Tesla, Volvo, Umicore, and Samsung SDI are system users.
- They are in communication with oversight bodies such as the OECD, RMI, and Drive Sustainability.

- The Re|Source Foundation institutionalizes the platform's governance and neutrality framework.

This structure enables not only a vertical supply chain but also ecosystem-based horizontal collaborations.

Relation to Regulation:

Re|Source directly targets the obligations under the EU's new Battery Regulation 2023/1542:

- Ethical sourcing requirement
- CO_2 footprint declaration
- Digital product passport

It operates in alignment with the OECD Due Diligence Guidance [2] and Global Battery Alliance standards. It can be said that this structure serves as an infrastructural "pre-figuration" of the regulations.

Strategic Benefits:

1. Thanks to the multi-actor trust model, data is not controlled by a single firm; it is pooled and governed by the industry.
2. Modularity and scalability for regulatory compliance: although limited to cobalt in the first stage, it appears capable of expanding to raw materials such as nickel and manganese in the future.
3. User-friendly interfaces: QR-code handheld devices provide easy data entry for field operators.
4. An approach of inviting rather than penalizing off-system actors (e.g., guides that encourage suppliers to digitalize without excluding them) is adopted.

Limitations:

- No full transparency policy: not all data are public; the platform adopts a "controlled transparency" model.
- Cost and infrastructure barriers: for small-scale miners, the system is costly and challenging in terms of digital access.
- Data-standardization gaps: API-level integration is limited for achieving full data compatibility with other systems.
- Traceability depends not only on the physical chain but also on data integrity, which cannot always be guaranteed.

Lessons for Türkiye:

- For a country like Türkiye, which is both a battery manufacturer and a raw-material importer, early integration with such consortia offers strategic competitive advantage.
- Sectoral associations (e.g., TAYSAD, BATTERY INDUSTRY PLATFORM) should be encouraged to establish joint systems based on digital traceability and responsible sourcing.
- Especially in second-life projects such as REBORN, tracking battery history should be made interoperable with such consortium-based systems.

- For supply-chain security, not only traceability but also technical elements such as data-sharing protocols and platform interoperability must be addressed.

6. STRATEGIC IMPLICATIONS FOR TÜRKİYE

In this section, our aim is to transfer the insights obtained from the preceding global case analyses to Türkiye's domestic electric vehicle and battery ecosystem and to develop concrete, applicable, and strategic recommendations.

In the EV battery supply chain, traceability has become decisive not only in terms of ethical and environmental responsibility but also in terms of strategic competitive advantage, foreign-trade compliance, and investment attractiveness. The European Union's new Battery Regulation No. 2023/1542 will require every battery placed on the market from 2027 onward to meet criteria such as carbon-footprint disclosure, responsible sourcing, and a digital product passport. Considering Türkiye's status as an automotive exporter within the scope of the EU - Türkiye Customs Union, as well as its rapidly growing domestic battery manufacturing capacity, this area becomes a strategic priority.

6.1. The Necessity of Blockchain-Based Traceability for Domestic Manufacturers

The journey of domestic actors such as TOGG, SIRO (the TOGG and Farasis joint venture), ASPİLSAN, Vestel, and Kontrolmatik–Pomega in developing electric vehicles and battery systems requires these companies not only to manufacture but also to establish a digital infrastructure that includes transparency, sustainability, and traceability criteria. Global examples have shown that:

- Traceability systems cannot be retrofitted; they must be designed in tandem with the product development process.
- PLM systems and blockchain infrastructure must interoperate, and EBOM and test data should be directly incorporated into the traceability chain.
- Instead of siloed data structures, open APIs and digital product passport formats should be supported.

6.2. Consortium Model and the Need for Shared Infrastructure

Consortium structures such as Re|Source are meaningful not only in terms of technology but also in terms of industry alliance and cost sharing. A similar structure in Türkiye could be designed, for example, under the leadership of TAYSAD, the Türkiye Battery Platform, or OSD.

Through such structures:

- Access to blockchain systems is facilitated for SMEs.
- Standard data formats and identity-verification structures are developed.
- The cost of compliance with EU regulations is shared at the system level rather than by individual firms.

6.3. Transition to Second-Life and Battery Passport Infrastructure

Within the scope of the EU Battery Regulation [11], the battery passport system has become mandatory and is being developed by different projects [7]. The REBORN project contributes to the development of digital traceability components throughout the battery life cycle by focusing particularly on the applications of this system in second-life and reuse scenarios [10]. For Türkiye to develop second-life systems (e.g., residential energy storage, utility-scale recovery), it must adopt such infrastructures.

In this context:

- Engineering data originating from PLM systems should be integrated into the battery passport.
- A blockchain-based verification system can be used for second-life classification to increase market trust.
- Active participation of Türkiye-based organizations in international projects such as REBORN will facilitate the internalization of this information infrastructure.

6.4. Proactive Compliance with Regulations and a Window of Opportunity

Türkiye should view the EU Battery Regulation not merely as an obligation but as an opportunity for technological leapfrogging.

Early adopters will gain priority access to high value-added markets with a “green supplier” status.
Traceability and sustainability documentation is becoming a new evaluation criterion for international financing, ESG investments, and public incentives.

Through blockchain-supported product passport implementations, it is possible to directly influence decisions by importing countries such as tax exemptions or exclusion from restrictions.

Overall, Türkiye’s battery and electric vehicle ecosystem should be strengthened not only with engineering solutions but also with digital infrastructure, supply-chain transparency, and blockchain integration. Otherwise, it will not be possible to be among the manufacturers that document transparency rather than those excluded by regulations.

7. CONCLUSIONS AND RECOMMENDATIONS

This study has revealed that traceability in electric vehicle battery supply chains is not merely a matter of technology; it is also an ethical, environmental, and strategic imperative. An examination of global examples shows that blockchain-based systems have initiated a significant transformation in supply chains by enabling transparent and reliable data sharing throughout the product life cycle.

Examples such as Tesla and Re|Source, Volvo and Circulor, and the Re|Source Consortium demonstrate that blockchain solutions formed through the collaboration of diverse sectoral actors provide traceability, accountability, and sustainability in many areas, from the ethical tracking of high-risk raw materials like cobalt to carbon-footprint disclosure.

The success of these systems depends not only on technological infrastructure but also on complementary factors such as multi-actor governance models, regulatory compliance, integration with PLM systems, and data security [15]. The bridge between Türkiye’s domestic production targets (TOGG, SIRO, Pomega, etc.) and its integration into global value chains is built precisely at this point.

Key Findings

Blockchain-based traceability structures integrated with PLM systems can record the entire life cycle of the product from engineering data to field performance.

In areas such as responsible sourcing, carbon footprint, and recycling, blockchain technology offers significant advantages in terms of both regulatory compliance and brand value.

Industry-consortium-based blockchain implementations create more sustainable models in terms of data security and multi-party acceptance.

With the EU Battery Regulation, the battery-passport requirement has turned data transparency from a mere expectation into a legal obligation.

Implementation Recommendations

In Türkiye, blockchain-based traceability solutions should be designed to cover the entire chain from battery cell to recycling, integrated with PLM and ERP systems.

Through institutions such as TAYSAD, OSD, and the Türkiye Battery Platform [14], a digital traceability network should be established among manufacturers and suppliers, and common platform standardization should be ensured.

Türkiye-based manufacturers should design battery-passport systems suitable for second-life scenarios, taking into account lessons learned from projects such as REBORN and Battery Pass.

Open-source, scalable, and cost-effective digital infrastructures that will facilitate access to blockchain solutions for small and medium-sized suppliers should be supported.

Carbon-footprint accounting and traceability data should be used not only for regulatory compliance but also for access to ESG investments, export advantages, and green finance.

In conclusion, blockchain technology offers a new paradigm for not only digitalization but also trust, ethical responsibility, and sustainability in the EV battery supply chain. Countries that adapt early to this paradigm shift will not only reduce external dependency but also assume high value-added roles in the global value chain. For Türkiye, realizing this transition not only at the level of manufacturing but also in terms of data transparency and digital traceability is a strategic necessity.

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A FRAMEWORK FOR SAFETY AND RISK FACTORS OF COMMERCIAL AND CIVILIAN UAVS

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Abstract

UAVs are increasingly used across a wide range of domains, including defense, government and commercial industries. Various hazards may threaten the safety and reliability of their operations. Especially increasing availability and use of drones in urban environments pose collision and falling risks and threaten humans and vehicles on the ground as well as other aircrafts in the airspace. Therefore, risk identification and assessment are critical components for the future of the rapidly growing UAV sector. This study aims to review the current body of research on risk and vulnerability factors in UAV operations and to develop a novel conceptual framework that integrates the findings into a structured and actionable perspective for improving UAV safety management. The proposed framework covers multiple hazards including operational malfunctions, pilot-related issues and external flight conditions such as weather events. Additionally, semi-structured interviews with experts and UAV operators are conducted to contextualize the risk framework and highlight practical challenges. The review also uncovers under-researched areas and trending risk themes such as u-space, cyber risks and safety protocols. This study provides a foundation for future research for safety practitioners and policymakers aiming to develop more resilient risk mitigation strategies.

Keywords: Drone, Flight safety, Risk classification, Risk identification, Unmanned aerial vehicle

Related topics: Risk management, Resilient logistics and supply chains

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are increasingly used across a wide range of areas including military operations, disaster management, space research, visual inspection, firefighting, weather forecasting and commercial operations. The UAV market share was $14.1 billion in 2018 according to a report published by Drone Industry Insights (Kapustina et al., 2021). UAV market share was expected to triple in size by 2024 and reach to approximately $45 billion by 2025 (Tezei et al., 2023). UAVs and drones suit a range of operations and use cases including delivery, monitoring, search and rescue, etc. UAVs may be categorized into different categories based on their usage area such as commercial, industrial, emergency, civilian, and military. Different companies started to integrate drones into their operations. Examples include autonomous last-mile delivery of Amazon and Walmart, oil and gas refinery inspection of Shell, drone shots of Netflix, etc.

Besides their advantages, UAVs also have some limitations and operational challenges. UAVs may operate remotely piloted, fully autonomous, or at different degrees of autonomy. Hazards may occur during flights due to a combination of technical, environmental, human and other factors. Especially increasing use of drones by civilians, which is a type of UAV, brings an increasing risk of accidents such as collision, loss of control, malfunctioning and fall. The use of drones in urban areas and flight restriction zones may create a high risk for people and vehicles. UAV risks may result in injuries, fatalities, and damage of properties or other aircrafts. Therefore, risk management is essential for safe and reliable drone flights and operations. UAV risk management is the identification, assessment, and mitigation of potential hazards and consequences related to UAV usage. UAVs may operate under different flight conditions. Therefore, both operational and environmental risks need to be integrated into the UAV path planning objectives.

UAV flight safety is a subset of UAV risk management and mainly focuses on operational precautions to prevent accidents during flights; e.g., pre-flight checks, regulatory compliance, pilot certificates, and maintenance. Flight safety is one of the most critical preventive components of UAV risk management. However, UAV risk management extends to pre-flight planning, post-flight data analysis, and emergency response. UAVs are exposed to numerous risks including technical failures, operator errors, weather conditions, regulatory non-compliance, and cybersecurity. All of these factors can significantly damage safety, reliability and success of UAV operations.

Given the complexity of UAVs and their critical importance for the modern industry, understanding and managing the diverse risks that affect UAV operations is essential. Therefore, this paper aims to propose a structured and comprehensive framework for identifying and categorizing risk factors related to UAV systems. A comprehensive review was conducted on existing literature, recent industry reports, and relevant news sources to identify different risk factors and emerging risk trends. Additionally, semi-structured interviews with drone operators and practitioners were conducted to gain practical insights and validate the identified risk factors. This multi-method approach ensures that the framework is grounded in both theoretical foundations and real-world experiences, enhancing its applicability in the industry.

By systematically categorizing these risk factors, the proposed framework seeks to provide a clear foundation for improving risk assessment, enhancing safety protocols and controls, and supporting decision-making processes. This conceptual framework intends to contribute to safer and more reliable UAV systems, delivering actionable insights and reducing the likelihood of accidents and operational disruptions.

The remainder of the paper is structured as follows. Section 2 outlines safety requirements and key risk management concepts for UAV operations. Section 3 presents the proposed conceptual framework addressing a diverse set of UAV risk factors and safety concerns. Section 4 presents different risk management perspectives, and Section 5 presents relevant standards and regulatory frameworks. Finally, Section 6 concludes the study and discusses potential directions for future research.

2 Risk Incidents and Safety Requirements for UAV Operations

Commercial and civilian use of UAVs are increasing tremendously in areas such as cargo delivery, surveillance, agriculture, infrastructure inspection, natural disaster relief, risk assessment, critical infrastructure security, public safety, and firefighting (Kapustina et al., 2021). The broad range of applications enhances operational efficiency and creates new opportunities; however, they face challenges including technical failures, route optimization under risks, energy limitation, security issues, and seamless integration with transportation networks (Höhrová, 2023).

The human factor is a predominant cause of accidents and accounts for approximately 70% of aircraft incidents (Göv & Kahraman, 2022). Although UAVs do not have people on board during flight like aircrafts, they involve tasks that depend on humans which inherently involve risks. The number of reported UAVs accidents is increasing dramatically year by year. While 50 UAV accidents were reported to the US Federal Aviation Administration (FAA) in February 2014, in December 2016 it was 200 (Akyürek & Eraslan). Dedrone (2025) dynamically monitors and shares drone violations in real-time across 50 different US cities through its sensor network. There are six different types of violations which are non-compliant night flights, exceeding the 400-foot maximum altitude limit (FAA 400 feet), unauthorized flights over correctional facilities, flights without Low Altitude Authorization and Reporting Authority (LAANC), unauthorized entry to event zones and Temporary Flight Restriction Areas (TFRs) and unauthorized flights over critical energy infrastructure. There is a notable rise in violations year by year. Total violations increased from 1,067,112 to 1,234,871 from 2023 to 2024 (Dedrone, 2025). In the violation records, the number of violations in each month of 2025 continues to be higher compared to 2024. Haugse (2022) observed 31,174 UAV flights in Norway and recorded 86 accidents and 68 incidents during a total flight duration of approximately 8,221 hours. The number and frequency of both incidents and accidents were evaluated while discussing the safety performances of the companies in Norway.

Various factors may lead to mishaps, incidents and accidents involving UAVs. Effective management of UAV risks is a crucial issue for ensuring safe and reliable operations. In the literature, risk is mainly defined as the product of the severity and frequency of the potential consequences. Therefore, severity and likelihood must be addressed to prioritize and mitigate the risks and enhance safety. Collision risks, operational challenges, cybersecurity threats, privacy concerns, legal and liability issues and regulatory limitations are considered as major risks when using UAVs (Hossin et al., 2025). According to a study conducted in Norway, the risk of UAVs was attributed to technical reasons (49.35%), human-related reasons (37.66%) and environmental reasons (12.99%) (Haugse, 2022). Electromechanical malfunctions such as inadequacy of ground control systems, poor navigation systems and software failures were determined as main technical risks causing accidents. Besides that, there are human-related reasons affecting the likelihood of accidents such as inattention, fatigue, confidence and vigilance of pilots and unfavorable organizational situations. Thirdly, reliability and flyability of UAVs gets affected notably by weather conditions, electromagnetic inference and environmental differences (Asghari et al., 2025; Rahmani & Weckman, 2024). The 2016 incident involving an Airbus aircraft with 132 passengers that was struck by a drone underscores the escalating safety risks posed by UAVs and reinforces the necessity for comprehensive risk assessment and mitigation strategies (Wild et al., 2016).

A number of prerequisites must be met to accomplish expected level of safety and establish appropriate flight regulations (lean, average, strict). On the technical side, some of the critical prerequisites may be listed as follows: collision avoidance, geofencing, path planning and compliance with no-fly zones, reliable communication link, operator training and certification. The stringency of flight regulations which enhances safety has a trade-off between increasing energy consumption and decreasing efficiency of routing (Mohamed & Mohamed, 2025). There are different attempts related to managing risks. To enhance safety operations and prevent potential risk of collision, Light Detection and Ranging (LiDAR) technology which increases the accuracy and precision in data capturing is used. LiDAR enables the creation of a high-resolution 3D map of the environment by using reflection of laser beams off surfaces and objects (Wanner et al, 2024).

The regulatory and legal side of UAV usage must be taken into consideration by governments and corporations to enhance safety. Management and control of UAV risks by regulators, will reduce the number of incidents and accidents (Allanson, 2018). The use of UAVs in environments where they may harm or threaten public safety and privacy should be restricted and regulated in terms of national security. In the USA, people who want to use UAVs commercially must provide appropriate conditions and have Remote Pilot Certificate (RPC) from the Federal Aviation Administration (FAA). Users must be at least 16 years old in the USA, not have a hearing impairment, able to read, write and speak English, physically and mentally competent, successfully pass the Aeronautical Knowledge Test, and pass the Transportation Safety Administration (TSA) security screening (Adnan & Khamis, 2022). While determining safety requirements of UAVs; hijacking, cyber security, data privacy, and location spoofing can be considered as the main potential vulnerabilities (Majeed et al., 2021). There is a gap in the literature due to the limited number of studies which concern the risk framework for UAVs. Creating adaptable and comprehensive frameworks which include cause-effect relationship between risks and accidents is crucial to prevent UAV incidents and accidents (Zhong et al., 2025). UAV usage also poses privacy risks including unauthorized photography and video recording. Digital forensic frameworks such as Conceptual Drone Forensic Framework (CDFF) and Drone Forensics Readiness Framework (DRFRF) have been developed to provide a guide for legal actions (Studiawan et al., 2025).

3 DEVELOPMENT OF A NOVEL FRAMEWORK FOR UAV RISK CATEGORIZATION

Despite the appealing benefits and opportunities provided by UAVs, there are important challenges and concerns of exploiting these vehicles at different operations. Drones may fail due to a number of reasons including mechanical problems, human error, or environmental factors. These failures may lead to serious safety problems and accidents resulting in injuries, fatality, and damage to buildings. A systematic risk assessment and mitigation strategy is essential to ensure safety, security and regulatory compliance of both commercial and personal UAVs and drones.

Risk identification is the first foundational step in effective risk management. A comprehensive risk categorization list would be very helpful in uncovering potential hazards such as technical failures, environmental factors and human errors that could lead to accidents or regulation violations. Therefore, this study proposes a comprehensive and structured risk categorization framework for all types of UAVs. A mixed-methodology approach was employed incorporating literature review and interviews with domain experts. The framework was finalized by conducting semi-structured interviews with two industry experts specializing in UAV operation, technology, and piloting. The proposed categorization of UAV risks and hazards is represented in Table 1. Basically, risks are categorized under the following five main categories: i) Technical risks, ii) Human-factor related risks, iii) Environmental risks, iv) Regulatory risk, v) Ethical and societal risks, vi) Safety challenges of industrial usage. This framework provides a foundation for risk detection and assessment steps, and may be used to facilitate development of risk management strategies.

The technological risks category includes many different factors due the reliance of UAVs on complex hardware and software systems. It covers the failures and malfunction of technical components, sensors, communication systems, or batteries. Practitioners generally refer to component reliability (e.g., motor, gyroscopes), power and communication/signal failures as the most common risks. Human-related risk may greatly affect the safety of operations. There may be serious operator errors due to inadequate training, unclear procedures, poor pre-flight controls, etc. Environmental factors such as weather, ground objects, and other manned or unmanned flying vehicles in the airspace may reveal safety and security problems for UAVs. Weather conditions including temperature, wind speed, and precipitation may adversely impact the flyability of UAVs, especially small drones. There are both technical and regulatory meteorological constraints and limits for safe operation.

Table 1: A Comprehensive Categorization of UAV Risks

CATEGORIZATION OF UAV RISKS	
TECHNICAL RISKS	
● Physical and mechanical risks ○ Propeller-related risks (e.g., Physical contact to propeller, incorrect assembly) ○ Moisture on the circuit board (rain, snow) ○ Sensor failures ○ Incorrectly configured or malfunctioning controller ○ Motor malfunction ○ Electromagnetic interference (EMI) problems ○ Camera and gimbal issues	● Communication problems ○ GNSS, WiFi, Mobile (4G, 5G) signal loss ○ Remote pilot system control problem ● Software problems ● Battery failure ● Payload-related risks ○ Reduced maneuverability ○ Reduced stability ○ Emergency landing risk ○ Increased energy consumption
HUMAN-FACTOR RELATED RISKS	
● Pilot/operator mistakes ○ Lack of training, experience or competency ○ Inattention and fatigue of pilots ○ Unclear operational procedures ○ Poorly designed user interfaces ● Air traffic controller mistakes	● Regulatory non-compliance ● Poor pre-flight planning (neglecting pre-flight checks, ignoring regulations, etc.) ● Poor team communication and organization structure ● Wrong emergency decisions under stress
ENVIRONMENTAL RISKS (Weather, Airspace, Flight Area and Flight Condition Problems)	
● Bad weather conditions (wind, hurricane, fog, etc.) ● Sunlight affecting electronic components and vision (Battery overheating, etc.) ● Environmental stress on mechanical components (dust, heat, icing, vibration, etc.) ● Electromagnetic inference ● Bird strike risk dangering flight safety	● Flight zone risk ○ Intrusion into restricted airspaces ○ Collision with other UAVs or manned aircrafts ○ Privacy risk ● Danger to urban areas and ground objects (dense regions, people, properties, vehicles, powergrids, etc.)
REGULATORY RISK	
● Violation of controlled airspace ● Lack of accepted international and national laws, guidelines and regulations ● Lack of safe flight corridors	● UAV noise regulation ● Unauthorised pilot or lack of UAV certification ● Liability risk
ETHICAL and SOCIETAL RISKS	
● Unauthorized surveillance and privacy violations ● Cybersecurity threats ● Location spoofing	● Disturbing birds and wild life ● Unclear legal responsibility for UAV accidents
SAFETY CHALLENGES OF INDUSTRIAL USAGE OF UAVs	
● Threats to the safety and security of drones due to dangerous work environment ● Hazardous payload handling	● Physical treats to human due to incorporating drones into the workplace

The fourth category is the regulatory risk which refers to uncertainty or non-compliance issues that arise from aviation laws, standards, and government regulations. For practitioners, it is one of the biggest non-technical risks in drone operations. Member States requested ICAO (International Civil Aviation Organization) to develop a regulatory framework for unmanned aircraft systems (UAVs) operating outside International Airspace (IFR). ICAO reviewed the existing UAV regulations of several States to identify commonalities and best practices that were compatible with the aviation framework and could be implemented by a wide range of States. The outcomes of this work were published in the form of ICAO Model UAV Regulations, entitled Parts 101, 102, and 149 (www.icao.int/UA/icao-model-uas-regulations).

The fifth category includes ethical and societal risks which covers privacy violations, surveillance misuse, safety concerns for humans, noise pollutants etc. The last category refers to the safety issues specific to industrial usage. Although UAVs are mainly used in military applications, there is a growing trend for industrial integration of drones in many different industries including construction, energy, and agriculture. Drones provide a wide range of opportunities such as surveying, surveillance, inspection, shipping, accessing remote areas, telecommunication (acting as a flying base station for improving cellular phone and Internet networks), etc. The incorporation of UAVs in the work environment may lead to physical danger for employees. UAVs have also started to be used in dangerous and dirty jobs or areas. This may negatively impact safety and security of UAVs. Jeelani and Gheisari (2021) examined the safety issues arising from UAV integration in construction projects and classified associated risks as physical hazards, attentional costs, and psychological impacts.

4 RISK MANAGEMENT IN UAVS

Following the risk identification, the next step is the analysis and assessment which involves evaluating the likelihood and potential consequences of identified risks. This prioritisation process helps to determine risk mitigation actions. Increasing use of UAVs reveals the necessity to develop and apply various risk mitigation measures. This section summarizes common methods used at different stages of UAV risk management.

4.1 Data-based risk assessment

Risks are generally assessed based on their probability of occurrence and severity of potential consequences. Rubio-Hervas et al. (2018) formulated a new risk metric for UAV operations considering stochastic nature of the environment and uncertainty in spatially distributed data. They used Gaussian process in their data-driven probabilistic modelling process and performed simulation analysis under realistic scenarios. Jiao et al. (2022) calculated the ground risk based on different parameters such as population density, ground impact, shelter factor considering buildings and trees, and fatality rate. They developed a dynamic ground risk assessment model using deep learning and kinetic models.

Different data sources may be used for UAV risk assessment including:

- i) Flight Operations Data and flight reports: flight logs, population density maps, LIDAR data, GPS coordinates, speed, battery status etc.
- ii) Operational Flight Data Monitoring (OFDM)
- iii) Weather data
- iv) Maintenance records (e.g., routine maintenance checklists)
- v) Historical accident records
- vi) Simulation data.

Various performance metrics are measured and monitored for the analysis and assessment of UAVs' quality, efficiency and risks. Table 2 summarizes some of the performance parameters used for UAVs' design, operations and flights.

Table 2: Some performance parameters for UAV design, operations and flights

UAV design	Flight Efficiency
● Vehicle weight ● Engine power ● Speed & Max speed ● Wing span ● Takeoff and Landing distance ● Payload capacity ● Endurance ● Control range ● Battery (discharge time, fuel/battery weight, etc.)	● Flight duration ● Flight speed ● Max airspeed ● Max altitude ● Max ground speed ● Remote controller range ● Energy efficiency (energy consumption, capacity etc.)

4.2 Risk mitigation actions

Risk mitigation includes the implementation of different strategies and technologies to reduce the likelihood and impact of risks throughout the entire lifecycle of UAVs. Effective risk management requires well-designed operational controls, maintenance protocols and risk prevention mechanisms. Some of the techniques that are used in risk identification and minimization for UAV operations may be listed as follows (Du et al., 2024; Almasi et al., 2024):

- Pre-flight checks
- Applying a risk-based airspace planning: developing a ground risk map & providing a separate airspace/corridor for UAVs
- Detailed flight performance analysis systems
- Risk-based flight path planning
- Developing risk maps for UAV flights and considering these assessments in UAV path planning to avoid risky areas
- Collision avoidance with stereo cameras and sensors
- Developing emergency landing systems
- Testing and certification (e.g., standards such as NIST, testing drones in various environments and extreme weather)
- Safe buffer distance

- Fault diagnosis and detection systems
- Education programs and pilot training
- Increasing awareness about risks

Flight permissions

Commercial drone operators must take permission from CAA before flying in controlled airspace. The expansion of UAV operations reveals the competition for airspace and necessitates the integration of UAVs into the national airspace. Kim and Bae (2022) proposed a methodology to analyse the capacity of UAV corridors by considering collision rate of the corridor (calculated based on Reich collision risk model) and failure rate of UAVs. They also generated a ground risk map to help selection of the UAV path by utilizing the databases of Seoul.

Fault diagnosis and detection systems

Operational reliability, safety and security of UAVs are critical issues that require the adaption of advanced fault diagnosis and detection systems. Fault diagnosis and detection systems play a critical role in ensuring reliability and safety of UAV operations. These systems are used to detect abnormal behaviours and faulty components for early identification of risks. They analyse flight data or signals (e.g., vibration patterns, noise) to detect potential faults. Bondyra et al. (2022) developed an acoustic fault detection system for multirotor UAV. The proposed system uses Artificial Neural Network to classify faults based on acoustic signals recorded with an onboard microphone.

Simulation

Various operating conditions and work scenarios can be simulated via 4D VR simulations for physical risk assessment of UAVs especially in construction. Characteristics of the real-world such as physical space, properties of materials and time can be replicated for developing control systems and optimizing paths for UAV flights. Also, building training systems for inspectors in a dynamic environment is one of the benefits of UAV flight simulations (Zhu et al, 2023). There are seven leading open-source simulation platforms for UAVs which are CoppeliaSim, Webots, USARSim, Gazebo, MORSE, ARGoS and MRDS. According to Chen et al. (2023), the selection of a simulation platform is influenced by eight key criteria: ease of use, system stability and maintainability, support for multiple sensors, the degree to which simulated environments reflect real-world conditions, diversity of built-in model libraries, accuracy and computational efficiency, availability of widely used applications and functions, and compatibility with multiple operating systems and programming languages.

Risk-based path planning

UAVs are exposed to various risks during their flights. Therefore, cost and distance minimization objectives are not enough especially in urban environments. Operational and external risk factors need to be integrated into the path planning process to provide a safe and secure flight. Various risk-based path planning models have been proposed in the literature. Hu et al. (2020) proposed a risk management model for UAV operations and a risk-based path planning method. They developed a risk cost map considering the risks coming from people on the ground, vehicles and manned aircraft, and used it in finding risk-cost-effective paths.

Developing a risk cost map helps to identify and avoid high-risk areas for UAVs. Figure 1 shows a risk cost map and an example risk-based and cost-effective path developed by Hu et al. (2020). Risk levels are represented by colour spectrum.

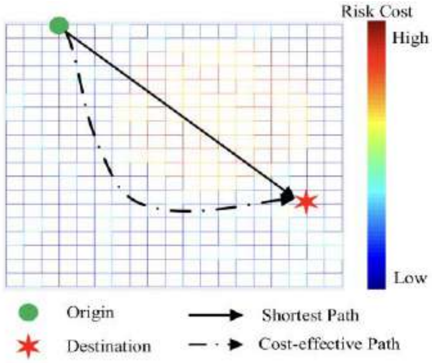

Figure 1: Risk cost map and an example cost-effective path avoiding high risk zones (Source: Hu et al., 2020).

5 Concluding Remarks and Future Research Directions

Given the increasing use of drones in both commercial and personal contexts, managing risks helps prevent accidents, protects privacy, and mitigates potential damages to people, property, and infrastructure. This study contributes to the UAV field by providing a structured framework for UAV risks. By integrating insights from a comprehensive literature review and expert interviews, this paper bridges theory and practical experience. The proposed risk categorization maps UAV-specific risk factors under technical, human-factor related, environmental, regulatory, ethical and societal, and industrial usage challenges headings.

As the usage of UAV and drone technology continues to evolve, several critical emerging risks must be managed. The first one is the airspace congestion, collusion risk and danger to bird/wildlife due to physical existence of an increased number of UAVs. Secondly, drones can access secure and restricted areas which may create a risk of violating privacy laws. Regulatory risk which refers to uncertainty or non-compliance issues that arise from aviation laws, standards, and government regulations poses a significant challenge for UAV operations. For practitioners, it is one of the biggest non-technical risks in drone operations. UAV technology develops much faster than regulatory frameworks. Additionally, since each country maintains its own aviation authorities and regulations, cross-border UAV flights represent a particularly complex challenge requiring multiple applications and special permissions (especially in logistics and humanitarian aid operations). Although global initiatives exist, their development and adaptation remain slow.

This study highlights both technical and non-technical risks in drone operations, underscoring the importance of a comprehensive approach to UAV risk management. While technical risks such as equipment failures, software malfunctions, and environmental conditions directly affect flight safety, non-technical risks—including regulatory uncertainty and societal concerns—pose significant barriers to wider adoption. The authors expect the proposed framework to provide a foundation for further research for developing advanced risk analysis methods, mitigation efforts, safety protocols, and regulatory frameworks.

Advances in autonomous systems, communication, and energy storage technology are expected to elevate UAVs into critical infrastructure across a wide range of industries. The complexity of associated risks will increase and new challenges such as cyber-physical security threats and cross-border regulatory conflicts will become more prominent. The ongoing development of UAV technologies presents both opportunities and risks, making effective risk governance a critical factor in realizing their full potential. Future road map of risk management in UAVs may be transformed with the following technologies; 5G and beyond, AI-based decision making, autonomous risk assessment, predictive maintenance, intelligent drone swarms, and global airspace integration.

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ASSESSMENT OF LOGISTICS SERVICE PROVIDERS USING DIGITALIZATION CAPABILITY AS A CRITERION

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Abstract

This study investigates the integration of digitalization capability as an objective and quantifiable criterion in the selection of logistics service providers, addressing the growing impact of digital transformation on supply chain management. Using a multi-criteria decision-making approach, ten candidate logistics service providers were evaluated across four criteria: price, delivery speed, service quality, and digitalization capability. The entropy method was employed to objectively determine the relative weights of each criterion, revealing that delivery speed and digitalization capability are the most influential factors in provider selection, while price and service quality are comparatively less significant. The weighted sum method was then used to calculate the overall scores and rankings of the providers, demonstrating that those excelling in both rapid delivery and advanced digital capabilities are most likely to be selected as partners. These results highlight the shift in organizational priorities towards technologically advanced, efficient logistics solutions in today's dynamic environment. The study offers a transparent, data-driven framework for both academics and practitioners, enabling more informed and future-ready partner selection decisions. Recommendations are provided for logistics firms and decision-makers to continuously adapt their evaluation criteria in line with digital trends and operational demands.

Keywords: Criteria weighting, digitalization capability, entropy method, logistics partner selection, multi-criteria decision making, weighted sum method.
Related topics: Digital transformation in logistics, Logistics service provider evaluation.

1. INTRODUCTION

Partner selection is a multifaceted process that significantly impacts organizational performance, particularly in collaborative environments. The criteria for selecting partners can vary based on the context, such as technological complexity or the nature of the collaboration. Partner selection is often a multi-stage process, where initial criteria include value offering and technological complexity (Chowdhury & Das, 2022). Selection criteria can be categorized into tangible (task-related) and intangible (partner-related) factors. Intangible factors such as trust, reputation, and management ability are crucial for long-term collaboration but are harder to quantify (Mat et al., 2014). Trustworthiness, the entrepreneur's profile, and company longevity are critical criteria identified through empirical research (Quatrin & Pereira, 2018).

While the outlined criteria provide a structured approach to partner selection, it is essential to recognize that the subjective nature of some intangible factors can lead to variability in decision-making. This highlights the need for a balanced evaluation that incorporates both objective metrics and subjective judgments.

In recent years, the rapid digital transformation in logistics and supply chain management has introduced new, measurable factors that can objectively distinguish between potential partners. Digitalization capability defined as the extent to which a logistics service provider leverages digital technologies to enhance operational efficiency, transparency, and innovation has emerged as a key criterion. Unlike traditional intangible factors such as trust, digitalization capability can be quantitatively assessed and systematically integrated into the partner selection process using multi-criteria decision-making (MCDM) methods. Therefore, an objective, data-driven approach that incorporates digitalization capability alongside conventional criteria is needed for effective partner selection in today's competitive logistics sector. This study adopts such an approach by employing the entropy method to determine objective criteria weights and the weighted sum method to rank logistics service providers based on multiple criteria, including digitalization capability.

2. LITERATURE REVIEW

For the selection of logistics service providers, organizations evaluate a combination of tangible and intangible criteria to ensure high operational efficiency and reliable partnerships. Tangible criteria often include price, delivery speed, and service quality, all of which are directly linked to performance outcomes and customer satisfaction (Lee et al., 2011). Additionally, the provider's technological capability and resource contribution such as network coverage and equipment play a crucial role, particularly in sectors requiring advanced infrastructure or specific expertise (Chowdhury & Das, 2022; Franco, 2010). On the intangible side, trust and integrity remain essential for fostering long-term collaboration and reducing operational risk (Mat et al., 2014; Mat et al., 2009). Organizational compatibility, referring to shared values and the ability to integrate with existing systems and cultures, is also a significant factor in successful provider relationships (Chowdhury & Das, 2022; Franco, 2010). Furthermore, a provider's previous track record and industry reputation serve as important indicators of their capability and reliability (Mat et al., 2009). In my view, while these criteria offer a comprehensive foundation for selection, the logistics sector's growing digitalization adds a new dimension to partner evaluation. The ability of service providers to leverage digital technologies such as real-time tracking, automation, and advanced data analytics has become increasingly relevant, enhancing transparency, operational efficiency, and overall competitiveness within supply chains.

Digitalization criteria in partner selection are essential for organizations aiming to enhance their competitive edge through effective collaborations. The integration of digital technologies into partner selection processes allows for a more nuanced evaluation of potential partners, considering both tangible and intangible factors. This overview will explore the key aspects of digitalization criteria in partner selection, including evaluation methodologies, the role of ICT tools, and the impact of digital expertise.

Table 1: Key Literature on Digitalization Criteria for Partner Selection in Logistics

Author/Year	Summary of the Study
Angeles and Nath, 2004	The study identifies "readiness for high-level EDI" and "EDI infrastructure" as critical factors in partner selection, emphasizing the importance of digital capabilities in fostering successful long-term relationships between customer and supplier firms engaged in electronic data interchange.
Lee et al., 2011	The paper identifies digitalization as a significant criterion in partner selection, emphasizing the need for e-business sub-contractor agencies and ISPs to assess partners' capabilities in implementing e-business solutions effectively, ensuring successful collaboration in the 'Bridging the Digital Divide of SMEs Project'.
Mat et al., 2014	The paper identifies that digitalization is a crucial criterion in partner selection, as it encompasses the use of Information Communication Technology (ICT) tools to evaluate both intangible factors like trust and tangible factors, enhancing collaboration efficiency and effectiveness.
Urbach and Ahlemann, 2016	Digitalization criteria in partner selection include the need for external skills and competencies not available in-house, as well as the ability to leverage IT outsourcing and cloud computing. Strategic partnerships become essential for implementing disruptive innovations effectively.
Wildhirt et al., 2018	The paper emphasizes the importance of actively engaging in co-innovation and systematically networking with start-ups, customers, and corporates. This approach ensures that digitalization initiatives are decoupled from established organizational patterns, fostering innovative ideas and digital know-how in partner selection.
Deepu and Ravi, 2021	The paper identifies digital technology enablers as a critical criterion in partner selection for Inter-Organizational Information Systems (IOIS). This factor, along with project completion time and financial resources, significantly influences the decision-making process for effective supply chain integration.
Maghakyan et al., 2021	The study emphasizes that audit partners with expertise in highly digitalized clients are preferred, as they command higher fees. This specialization in digitalization is distinct from industry-specific knowledge, highlighting its importance in partner selection for audit firms.
Aghimien et al., 2022	The paper emphasizes that digitalization criteria in partner selection for construction organizations should focus on technological capabilities, collaborative tools, and the ability to adapt to digital processes, ensuring effective integration and innovation in the digital transformation journey.
Mohammed et al., 2022	The digitalization criterion in partner selection involves evaluating suppliers based on their integration of digital technologies, which enhances supply chain resilience and efficiency. This framework aids purchasing managers in making informed decisions that align with modern supply chain demands.

Gao et al., 2024	The paper emphasizes the importance of digitalization criteria in selecting digital supply chain partners, integrating fuzzy information and entropy measures to assess partners' capabilities in achieving digital transformation, ensuring alignment with sustainable development and circular economy principles.

Table 1 summarizes key academic studies that have examined the role and importance of digitalization-related criteria in partner selection within the logistics sector. The literature demonstrates a clear trend toward the increasing relevance of digital capabilities such as EDI infrastructure, ICT tool integration, external IT competencies, and digital co-innovation in both evaluating and selecting logistics partners. Each study highlights different dimensions of digitalization, reflecting its multifaceted impact on supply chain collaboration, operational efficiency, and strategic alignment.

3. ORIGINALITY OF THE STUDY

This study contributes to the logistics and supply chain management literature by objectively incorporating digitalization capability as a quantifiable and decision-influencing criterion in the selection of logistics service providers. Unlike previous studies that have often discussed digitalization qualitatively or as a secondary consideration, this research applies the entropy method to calculate objective weights for digitalization and other key criteria, reflecting the true variability and importance of each factor. By combining entropy-based weighting with the weighted sum method, the study offers a transparent, reproducible, and data-driven approach for evaluating and ranking potential logistics partners. This methodology not only highlights the growing significance of digitalization capability in logistics partner selection but also provides a practical framework for decision-makers facing the challenges of digital transformation and increased complexity in modern supply chains. The use of simulated data further demonstrates the applicability of the approach in situations where real-world data may be inaccessible, making the study relevant for both academics and practitioners.

4. PROBLEM DEFINITION

In today’s rapidly evolving logistics sector, the selection of appropriate logistics service providers has become increasingly complex due to the proliferation of digital technologies and changing customer expectations. While traditional criteria such as price, delivery speed, and service quality remain essential, the growing impact of digitalization demands the integration of new, objectively measurable criteria into the decision-making process. However, many existing studies continue to assess digitalization capability subjectively or fail to account for its true variability among potential partners. This creates a significant gap in the literature and in practice, as decision-makers lack transparent, data-driven methods to accurately evaluate and prioritize logistics partners according to their digitalization capability. Therefore, there is a critical need for a systematic approach that incorporates digitalization as a quantifiable criterion and provides objective weighting in the partner selection process, enabling organizations to make more informed and future-ready decisions.

Table 2: Criteria Values for Candidate Logistics Service Providers

Logistics Service Provider	Price (₺)	Delivery Speed (days)	Service Quality (10)	Digitalization Capability (10)
LSP1	22,000	3	8	6
LSP2	25,000	4	7	8
LSP3	24,000	2	6	9
LSP4	23,000	3	7	7
LSP5	21,000	5	5	5
LSP6	28,000	4	8	9
LSP7	27,000	6	9	6
LSP8	24,500	2	7	8
LSP9	26,000	5	6	7
LSP10	22,500	3	8	7

The aim of this analysis is to select the most suitable logistics service provider from among the candidates, based on the criteria values presented in the Table 2.

5. SOLUTION APPROACH / METHODOLOGY

This study utilizes quantitative multi-criteria decision-making (MCDM) framework to identify the most suitable logistics service provider among a set of alternatives. The methodology begins with the identification of four key selection criteria; price, delivery speed, service quality, and digitalization capability based on an extensive review of the literature.

To ensure the practical applicability of the proposed approach, simulated data representing ten candidate logistics service providers are used. All criteria values are first normalized to account for differences in units and scales, as well as to ensure that higher or lower values are consistently interpreted according to their desirability.

The entropy method is then applied to objectively determine the weight of each criterion, assigning higher importance to those with greater variability across providers. Subsequently, the weighted sum method is used to calculate an overall score for each provider by multiplying their normalized scores by the corresponding criterion weights and summing the results. Finally, the logistics service providers are ranked according to their total scores, and the provider with the highest score is selected as the optimal choice. This integrated approach offers a transparent, data-driven, and reproducible framework for effective partner selection in the context of digitalizing logistics environments.

The entropy method is a versatile analytical tool used across various fields to assess and optimize systems by quantifying uncertainty and information content. It operates on the principle of measuring the disorder or randomness within a dataset, which can enhance decision-making processes and improve system performance (Bostanci and Ocakçi, 2009; Zhang et al., 2011; Wu et al., 2011)

The entropy method steps (Akçakanat et al., 2017):

Step 1: In order to eliminate the effects of incomparable index dimensions arising from different measurement units in the decision matrix, the indices are standardized using various methods. For benefit and cost indices, the criteria are normalized according to equations (1) and (2):

$$r_{ij} = \frac{x_{ij}}{(x_{ij})} \qquad (i = 1, \dots m; j = 1, \dots\dots n) \qquad \textbf{(1)}$$

$r_{ij} = \frac{min(x_{ij})}{x_{ij}} \qquad (i = 1, \ldots m; j = 1, \ldots\ldots n)$
(2)

Step 2: To remove inconsistencies due to different units of measurement, normalization is applied and P_{ij} is calculated as follows:

$P_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}; \quad \forall j$
(3)

Where:
i: alternatives
j: criteria
P_{ij}: normalized values
a_{ij}: given benefit values

Step 3: In this step, the entropy value E_j is computed using equation (4):

$E_{ij} = -k \sum_{i=1}^{m} \quad [\, P_{ij} \; ln\, ln\, (\, P_{ij}\,)] \,; \quad \forall j$
(4)

Where:
k=(ln n)$^{-1}$: entropy coefficient
E_j: entropy value for criterion j
P_{ij}: normalized value

Step 4: In the fourth step, the degree of divergence or uncertainty for each criterion, d_j, is calculated using equation (5):

$d_j = 1 - E_j \;; \quad \forall j$
(5)

Step 5: Finally, the weight of each criterion wjw_jwj is determined as follows:

$w_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \quad ; \forall j$
(6)

The weighted sum method steps (Marler and Arora, 2010):
$U = \sum_{i=1}^{k} \quad w_i F_i \,(x)$
(7)

Alternative selection was carried out under the findings heading using 7 formulations.

6. FINDINGS
Normalization of values;

- Price: min/value (low price is good)

- Speed: min/value (low day is good, fast delivery)
- Quality: max/value (high is good)
- Digitalization: max/value (high is good)

min Price = 21000, min Speed = 2, max Quality = 9, max Digitalization = 9

Table 3: Normalization of Values

Logistics Service Provider	Price	Delivery	Quality	Digitalization
LSP1	21/22=0.955	2/3=0.667	8/9=0.889	6/9=0.667
LSP2	21/25=0.840	2/4=0.500	7/9=0.778	8/9=0.889
LSP3	21/24=0.875	2/2=1.000	6/9=0.667	9/9=1.000
LSP4	21/23=0.913	2/3=0.667	7/9=0.778	7/9=0.778
LSP5	21/21=1.000	2/5=0.400	5/9=0.556	5/9=0.556
LSP6	21/28=0.750	2/4=0.500	8/9=0.889	9/9=1.000
LSP7	21/27=0.778	2/6=0.333	9/9=1.000	6/9=0.667
LSP8	21/24.5=0.857	2/2=1.000	7/9=0.778	8/9=0.889
LSP9	21/26=0.808	2/5=0.400	6/9=0.667	7/9=0.778
LSP10	21/22.5=0.933	2/3=0.667	8/9=0.889	7/9=0.778

For P_{ij} the sum of each column is calculated, then each cell is divided by the column total.

The sum for Price column is:
0.955 + 0.840 + 0.875 + 0.913 + 1.000 + 0.750 + 0.778 + 0.857 + 0.808 + 0.933 = 8.709
LSP1, P_{ij} for Price: 0.955 / 8.709 = 0.110
Continue in a similar manner for all cells (Table 4).

Table 4: Ratio Matrix (P_{ij})

Logistics Service Provider	Price P_{ij}	Speed P_{ij}	Quality P_{ij}	Digitalization P_{ij}
LSP1	0.110	0.109	0.109	0.080
LSP2	0.096	0.081	0.095	0.107
LSP3	0.100	0.163	0.081	0.120
LSP4	0.105	0.109	0.095	0.094
LSP5	0.115	0.065	0.068	0.067
LSP6	0.086	0.081	0.109	0.120
LSP7	0.089	0.054	0.122	0.080
LSP8	0.098	0.163	0.095	0.107
LSP9	0.093	0.065	0.081	0.094
LSP10	0.107	0.109	0.109	0.094

$$E_{ij} = -k \sum_{i=1}^{m} \left[P_{ij} \; ln\, ln\, (P_{ij}) \right] ;$$

n = 10, ln(10) ≈ 2.3026

Table 5: Entropy Method Results for Criteria Weighting

Criterion	Entropy (E_j)	Info Difference (d_j)	Weight (w_j)
Price	0.9983	0.0017	0.0395
Speed	0.9720	0.0280	0.6670
Quality	0.9943	0.0057	0.1353
Digitalization	0.9934	0.0066	0.1582

The Table 5 presents the entropy values, information differences, and computed weights for all criteria. These weights were derived objectively from the data and will be used for evaluating and ranking the logistics service providers.

7. FINDINGS

The results of the entropy method revealed that among the four selection criteria; price, delivery speed, service quality, and digitalization capability, **delivery speed** exhibited the highest weight (0.6670), indicating that variations in delivery speed among logistics service providers play the most decisive role in the selection process. This was followed by digitalization capability (0.1582) and service quality (0.1353), while price had the lowest weight (0.0395). These findings suggest that, for the given data set, differences in speed and digitalization among providers are more significant and influential than cost considerations, which may reflect the increasing demand for rapid and digitally enabled logistics solutions in today's market.
Criteria Weights:

- Price: 0.0395
- Speed: 0.6670
- Quality: 0.1353
- Digitalization: 0.1582

Table 6:Normalized Values for all LSPs

LSP	Price	Speed	Quality	Digitalization
LSP1	0.9545	0.6667	0.8889	0.6667
LSP2	0.8400	0.5000	0.7778	0.8889
LSP3	0.8750	1.0000	0.6667	1.0000
LSP4	0.9130	0.6667	0.7778	0.7778
LSP5	1.0000	0.4000	0.5556	0.5556
LSP6	0.7500	0.5000	0.8889	1.0000
LSP7	0.7778	0.3333	1.0000	0.6667
LSP8	0.8571	1.0000	0.7778	0.8889
LSP9	0.8077	0.4000	0.6667	0.7778
LSP10	0.9333	0.6667	0.8889	0.7778

Table 7: Weighted Total Score Calculation (WSM) for each LSP

LSP	WSM Score
LSP1	0.708
LSP2	0.695
LSP3	0.891
LSP4	0.747
LSP5	0.494
LSP6	0.734
LSP7	0.589
LSP8	0.895
LSP9	0.582
LSP10	0.752

Utilizing the entropy-derived weights, the weighted sum method was applied to evaluate and rank all logistics service providers. For each provider, their performance on each criterion was first normalized, and then multiplied by the corresponding entropy-based weight. The total weighted scores demonstrated that **LSP8** and **LSP3** achieved the highest overall rankings, with scores of 0.895 and 0.891 respectively, closely followed by LSP10. The findings indicate that providers excelling in both rapid delivery and high digitalization capability are more likely to be preferred, even if their prices are not the lowest among the alternatives. Overall, the results confirm the growing importance of digitalization and operational speed in logistics partner selection, supporting a shift towards more integrated and technologically advanced supply chain strategies.

8. Conclusions and Recommendations

This study demonstrates that incorporating digitalization capability as a core criterion in the selection of logistics service providers provides a more comprehensive and realistic assessment framework, especially in the context of increasing digital transformation within the industry. The findings indicate that delivery speed and digitalization capability are the most influential factors in provider selection, surpassing traditional considerations such as price and service quality. This shift highlights the evolving expectations of customers and organizations, who now prioritize fast, technologically enabled solutions in logistics operations.

The application of the entropy method for objective weighting, combined with the weighted sum method for ranking, offers a transparent and replicable decision-making approach that can be adapted by both researchers and practitioners. By leveraging real or simulated data, organizations can identify the most suitable logistics partners that align with their operational priorities and digital strategies.

Based on the findings, it is recommended that logistics firms seeking to enhance their competitiveness invest in digital transformation initiatives, such as real-time tracking systems, automation, and data-driven process optimization. Decision-makers are also encouraged to regularly review and update their selection criteria to ensure they remain relevant to emerging trends and customer demands. Future research can extend this framework by incorporating additional criteria, analyzing larger or real-world data sets, or comparing different multi-criteria decision-making methods to further validate and generalize the results.

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INTEGRATION, INNOVATION AND DIGITALISATION IN THE SUPPLY CHAIN FOR SUSTAINABILITY: A MODEL PROPOSAL BASED ON LITERATURE

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Abstract

Purpose:
This study aims to reveal the strategic contribution of this triple structure to sustainability performance by addressing the interactions of integration, innovation and digitalization in sustainable supply chain management in a holistic theoretical framework. In contrast to the scattered approaches in the literature, this study aims to fill an essential theoretical gap by emphasizing the complementarity between factors.

Study design/methodology/approach:
This study was conducted using a qualitative approach and structured using a conceptual analysis method based on a comprehensive literature review. Hypotheses were developed in line with the theoretical and empirical findings in the literature and designed to create a theoretical framework to explain sustainable supply chain performance.

Findings:
The study reveals that supply chain integration, digitalisation and innovation directly and positively impact sustainability performance. These three elements contribute to firms increasing resource efficiency, reducing environmental impacts and creating more flexible and innovative supply processes. The findings support the theoretical hypotheses and show that these factors complement sustainable supply chain management.

Originality/value:
This study goes beyond the fragmented approaches in the literature by bringing together the holistic impact of integration, digitalisation and innovation on sustainability in a theoretical framework. Its model provides a unique, multidisciplinary perspective on sustainable supply chain strategies for academic research and practitioners. It also provides a strategic roadmap to guide companies at the sectoral level on sustainability-oriented supply chain design.
Keywords: Sustainable supply chain, Supply chain integration, Digitalisation, Innovation

Related topics: List about two (maximum of four) topics from the congress topics list, in order of relevance, separated by commas.

1. INTRODUCTION

Today, firms face various challenges in gaining a competitive advantage in an increasingly complex global business environment with rapidly changing customer expectations. In this dynamic context, the possibilities offered by digital technologies increase accuracy and transparency in supply chains, enabling managers to monitor operational processes more effectively and improve overall performance (Le et al., 2024).

However, the structural transformation by digitalisation also brings some complexities and potentially negative impacts on performance. At this point, supply chain management stands out as a strategic tool in overcoming these challenges and ensuring systematic integration. One of the basic principles of supply chain management is the integrated production and information flow management throughout the process. In this context, supply chain integration refers to the extent to which not only the internal processes of an organisation, but also the activities of suppliers, customers and other external stakeholders are carried out in harmony (Hosseini Baharanchi, 2009). Furthermore, Yıldız & Sayın (2020a) emphasise that integration plays a critical mediating role by revealing that supply chain knowledge management significantly affects supply chain performance through supplier integration.

Supply chain management is not only limited to ensuring economic efficiency, but also plays a critical role in line with environmental and social sustainability goals. Beyond increasing operational efficiency, the concept of sustainability reflects a holistic approach that redefines the relationship of businesses with the environment and society. Accordingly, management theories and principles for sustainable supply chains are constantly evolving; this development necessitates reviewing current practices and identifying strategic goals for the future (Xu et al., 2019). In the literature, it is suggested that downstream integration and strategic alignment of supply chains in terms of environmental sustainability will improve the environmental performance of firms. In addition, the strong relationship between environmental management and supply chain integration has been demonstrated by various studies (Tarifa-Fernandez et al., 2023).

Evaluating sustainable supply chain performance involves enhancing resource utilization efficiency and reducing the consumption of materials, energy, and water. In this setting, formulating eco-efficient methods is essential for mitigating the environmental implications of supply chain activities. Furthermore, supply chain managers aiming to fulfil stakeholder expectations and align with business strategy are adopting innovative methods, including waste management, circular economy techniques, and low-carbon technologies. Within this framework, it is unavoidable that future supply chains will be organized using sustainable strategies that emphasize energy efficiency and reduce carbon footprint (Tebaldi et al., 2018).

Current supply chain methods are inadequately connected with environmental, social, and economic sustainability objectives, representing a significant issue for enterprises and society. The absence of integration in supply chains, inadequate adoption of innovative methods, and insufficient internalization of digital technology can adversely impact sustainability performance. The primary issue of the study pertains to the impact of supply chain integration, innovation, and digitalization on sustainability performance, as well as integrating these three elements into a theoretical framework.

This study seeks to analyze the interplay of these three aspects with sustainability through a systematic methodology. Limited research has examined the synergistic effects of supply chain integration, innovation, and digitization on sustainability performance, which are often addressed in isolation within the literature. This study seeks to address this deficiency in the literature and establish a theoretical framework for sustainable supply chain management. The study aims to examine the roles of supply chain integration, innovation, and digitalization in enhancing sustainable performance, elucidate the interconnections among these three components, and assess their practical ramifications for enterprises.

In terms of scope, the study addresses sustainability-oriented supply chain management at the theoretical level and focuses on environmental, social and economic sustainability dimensions. In the first stage, the concepts of supply chain integration, innovation, and digitalisation are defined in the context of the literature, and the effects of these elements on sustainability performance are discussed within the framework of a theoretical model.

In this direction, the study seeks answers to the following main research questions:

RQ1. How and through which mechanisms does supply chain integration affect sustainability performance?
RQ2. In which dimensions does innovation play a transformative role in sustainable supply chain management?
RQ3. How does digitalisation make supply chain processes more sustainable?
RQ4. Can the interactional structure of these three dynamics make a holistic contribution to sustainability performance?
These research questions form the theoretical basis of the hypotheses developed in the study and enable a multidimensional assessment of sustainable supply chain management. Finally, in light of the findings, recommendations for the academic literature and the business world are developed.

2. LITERATURE REVIEW

In today's business world, it has become increasingly imperative for organisations to achieve competitive advantage within their internal structures and through collaborative strategic partnerships with supply chain stakeholders (Stock et al., 2010). With the acceleration of globalisation, intensification of competition and complexity of market conditions, many activities, processes and services have started to be outsourced. These developments have led supply chains to become structurally more complex and inter-organisational interactions to increase. In this context, inter-enterprise integration and coordination along the supply chain are among the key components of supply chain management (Bastas & Liyanage, 2018). Many studies in the literature have reached a consensus on the definition of supply chain: A supply chain is defined as a network of at least three organisations (companies, institutions or individuals) that are directly involved in the back-and-forth flow of products, services, financial resources and information in the direction of the final customer or vice versa (Gibson et al., 2005). The main objective of supply chain management is to maximise the competitiveness of the entire chain while increasing customer satisfaction. In line with this goal, inter-business and inter-functional integration is critical. Today, competition is not between individual businesses, but between integrated supply chains (Stadtler, 2014). An integrated supply chain is based on organisational cohesion in all processes from the procurement of raw materials to the timely delivery of finished products to customers, and these processes are coordinated by continuous information flow. Thus, all chain links establish a synchronised interaction between demand forecasts and actual demands (Hosseini Baharanchi, 2009). However, the increasingly complex structure of supply networks and the increasing need for transparency and flexibility require businesses and sectors to restructure their supply chain processes to maintain their competitive advantage. Increasing product diversity on a global scale and intensifying demand fluctuations stand out as important obstacles that negatively affect the ability of supply chain stakeholders to balance supply and demand. Especially in the supply processes of sensitive and high-value products, preventing physical damage that may occur in logistics stages is of strategic priority. In conventional supply chain management systems, product loss during transport, delivery delays, counterfeiting, authentication inadequacies, data traceability deficiencies and data reliability issues are frequently reported operational risks (Meidute-Kavaliauskiene et al., 2021).

2.1. Supply Chain Integration

One of the basic principles of supply chain management is the integrated execution of production and information flow throughout the entire process. Supply chain integration refers to the harmonious coordination of not only the internal activities of the business, but also the processes carried out with suppliers, customers and other stakeholders. An integrated supply chain ensures organisational alignment at all stages, from the procurement of raw materials to the customer's timely delivery of the final product. In this process, a continuous and uninterrupted flow of information allows synchronisation of demand forecasts and actual demands (Hosseini Baharanchi, 2009).

Supply chain integration is considered at two basic levels: (1) tactical coordination based on delivery information (material flows and operational planning), (2) strategic co-operation based on joint development of product and service offerings (Wiengarten & Longoni, 2015). Effective integration enables businesses to deliver products at an appropriate cost, in the correct quantity, and to the desired location. It also requires all stakeholders to work in a coordinated manner (Gunasekaran & Ngai, 2004). Lack of integration can lead to chain imbalances such as "bullwhip effect" and cause problems such as inventory fluctuations, cost increases and decreases in service quality (Trkman & McCormack, 2009).

The ultimate goal of integration is to ensure the efficient flow of information, financial resources, and decisions throughout the supply chain to deliver maximum value to the customer at a low cost and high speed. The literature considers supply chain integration in three dimensions: internal, supplier, and customer integration (Kang et al., 2018).

Internal integration refers to the methodical exchange of information and operational coordination among departments inside the organization. Coordinating divisions like as production, logistics, procurement, and marketing minimizes resource wastage and enhances operational agility (Flynn et al., 2010). An efficient internal integration allows units to align with corporate strategy and respond more swiftly to customer demands. Enhancing interdepartmental information flow reduces expenses and establishes a durable competitive advantage by accelerating the order-to-delivery process (Basnet, 2013).

Supplier integration seeks to align outsourced processes with internal operations (Chen et al., 2009). This integration includes information exchange and operational collaboration with strategic suppliers. Supplier integration enables companies to comprehend suppliers' capacity limitations and capabilities, foresee bottlenecks, and optimize production planning. It facilitates the advancement of new solutions in product design, process development, and quality management, while enhancing supply chain performance by establishing long-term partnerships (Schoenherr & Swink, 2012).

Customer integration is designed to foster profound collaboration and information exchange with strategic clients. This integration enables organizations to analyze market dynamics more precisely, respond swiftly and efficiently to client needs, and secure a competitive edge (Munir et al., 2020). An in-depth examination of client profiles enhances customer connections and boosts loyalty. It also allows manufacturers and service providers to create bespoke solutions tailored to customer requirements and fosters innovation processes (Koç, 2021).

2.2. Supply Chain Innovation

The importance of the strategic relationship between supply chain management and innovation is increasingly recognised. However, the academic literature in this area has not yet reached a mature level, and its theoretical framework has not been fully clarified. Existing studies provide numerous empirical findings that emphasise supply chain stakeholders' critical involvement in innovation processes. However, predictive and systematic studies on how this involvement will evolve in the future, in which interdisciplinary areas it will be concentrated, which technological transformations it will be affected by, and what kind of management paradigm it will settle in are still limited. This situation is an important gap in the literature (Seyhan et al., 2021).

Innovation is a critical competence that provides a competitive advantage to businesses, especially in market environments where consumer preferences change rapidly and product differentiation is limited. This advantage is based on innovation's dynamic flexibility in strategic decision-making processes. Organisations with innovative capacity can respond faster to market changes, develop alternative strategies and implement these strategies rapidly (Seo et al., 2014).

Supply chain innovation is a strategy methodology that adjusts to environmental risks and more efficiently addresses consumer expectations by altering organizational processes through digital technology (Wong & Ngai, 2019). Ojha et al. (2016) characterize this process as a relational phenomenon necessitating inter-organizational collaboration, knowledge exchange, and cultural adaptation in addition to technology transformation. Lee et al. (2014) regard supply chain innovations as strategic instruments that enhance the dynamic interactions among all stakeholders within the supply network, asserting that these innovations afford firms considerable flexibility to improve operational efficiency, lower costs, uphold quality, and expedite delivery times in swiftly evolving market conditions.

2.3. Digitalisation in Supply Chain

The current digital revolution has fundamentally altered how humans communicate and engage with their surroundings. A diverse array of innovative technologies, including mobile technology and artificial intelligence-enabled systems, transform social information processes and data sharing dynamics. This technology development profoundly impacts individual lives and all industrial sectors, with supply chain management and logistics operations being heavily influenced by this change (Büyüközkan & Göçer, 2018).

The digital supply chain is characterized as a customer-centric and data-driven system; its globally integrated structure and dynamics, bolstered by advanced technologies, facilitate the delivery of products and services in a more accessible, rapid, and cost-effective manner (Seyedghorban et al., 2020).

Hartley & Sawaya (2019) highlight the growing significance of digital technologies in supply chain operations, particularly new solutions like robotic process automation, artificial intelligence, machine learning, and blockchain. These technologies are extensively employed to enhance operational efficiency, minimize human errors, and fortify decision support systems.

Wang et al. (2019) examines the present effects and prospective future changes of blockchain technology on supply chain applications, highlighting its benefits, particularly in transparency, security, and traceability. Kittipanya-Ngam & Tan (2020) investigated the impact of digitalization on the food supply chain and found that this change enhances connectivity, modernity, and adherence to customer expectations and regulatory requirements.

Ivanov et al. (2018) assert that digitalization enhances both efficiency and inventive adaptability within supply chains. This adaptability allows supply chains to react swiftly and efficiently to unforeseen alterations and emergencies. The literature addresses both the beneficial elements of digitalization and its potential negative consequences. Son et al. (2021) examine the obstacles and hazards associated with digital supply chain applications, highlighting the necessity for vigilance, particularly for data security, investment expenditures, and staff adaptation.

3. THE IMPACT OF INTEGRATION, INNOVATION AND DIGITALISATION ON SUSTAINABILITY

In today's economic dynamics, innovation is key to ensuring sustainable development and increasing social welfare. Regarding businesses, innovation is accepted as a strategic tool to increase productivity, maximise profitability and improve overall corporate performance (Can & Eriş, 2013). Innovation has become indispensable for organisations that want to succeed in global market conditions where competition intensifies. Today, businesses gain a competitive advantage by implementing existing innovations or shaping the sector with radical innovations (Seyhan et al., 2021).

Austrian economist Joseph Schumpeter introduced the concept of innovation to modern economic theory. In his work Theorie der wirtschaftlichen Entwicklung (The Theory of Economic Development) published in 1912, Schumpeter argued that innovation is the main driving force of economic growth and classified this process under five basic categories (Dinler, 2016; transmitted by Karakaş & Güçlü, 2018): Development of new products not previously available in the market, application of innovative methods in production processes, discovery of new markets or development of creative marketing strategies, procurement of new raw material resources or intermediate goods, radical transformations in organisational structures. This quintet structure reveals that innovation should be handled in technical, strategic, marketing and managerial dimensions.

On the other hand, there is a strong and multi-layered relationship between supply chain management and sustainability. Sustainability represents a comprehensive understanding of the operational factors that increase profitability and the environmental and social impacts of these activities. In this context, sustainable supply chain management contributes to operational efficiency and is critical in creating social awareness and supporting ecological responsibility (Govindan et al., 2014).

Incorporating sustainability concepts into supply chain operations enables organizations to safeguard their long-term assets. Within this framework, it is essential to mitigate environmental consequences, embrace concepts of social responsibility, and implement an ethical management strategy throughout all activities, from internal operations to external stakeholder relations. This comprehensive approach plays a crucial role in the strategic change necessary for sustainable development, particularly in supply chain management (Kılıç, 2024).

3.1. Digitalisation, Integration and Innovation

The intense competitive pressure and swiftly evolving market conditions need that manufacturing organizations embrace innovation as a fundamental strategic capability to attain enduring success. In this setting, it is essential to integrate Total Quality Management (TQM) techniques with innovation processes. Research indicates that the principles of TQM, including customer orientation and continuous improvement, enhance organizations' innovative capabilities, hence favorably influencing corporate performance. The methodical methodology of TQM facilitates the efficient implementation of innovative concepts, while creative solutions derived from innovation enhance the efficacy of quality management operations (Yıldız & Aytekin, 2019).

Digital innovation denotes the methodical incorporation of digital technologies into the innovation processes of organizations. It provides companies with benefits such as the reduction of new product development cycles, the aggregation and analysis of data from many sources, and the ability to address customer demands swiftly (Le et al., 2024). Technologies include big data analytics, artificial intelligence, cloud computing, and IoT, facilitated by digitalization, enhance competitive advantage by fostering expedited, adaptable, and customer-centric innovation processes. In this context, a digitalisation strategy, IT integration, and IT agility are essential methods that improve innovation performance by bolstering organizations' potential for process innovation (Tajudeen et al., 2022). Digitalization allows companies to enhance their algorithms, manufacturing methods, service provision, and strategies by fortifying data-driven innovation processes, thereby securing a competitive edge. Data, regarded as a "core economic asset," provides organizations with a substantial competitive advantage and is a key resource that propels innovation (Stucke & Ezrachi, 2020).

Conversely, supply chain integration emerges as a vital factor facilitating innovation. Yıldız & Sayın (2020b) investigated the influence of customer integration on firm performance, identifying product innovation capacity as a mediating variable, and showed that customer integration significantly and positively affects both innovation capacity and firm performance. The results indicate that incorporating consumer information and feedback into innovation allows organizations to create market-relevant, value-generating solutions.

Integrating items, financial movements, and information in contemporary supply chains is essential. The infrastructure established by digitalization facilitates real-time data exchange and collaboration across supply chain participants, fostering agility and adaptability in innovative processes. Thus, organizations may swiftly adapt to fluctuating market conditions, create tailored solutions for customers, and enhance operational efficiency (Zimmermann et al., 2016).

Consequently, digitalization and supply chain integration enhance the velocity and efficacy of innovation, rendering it a fundamental aspect of the entire organizational framework, allowing enterprises to attain sustainable competitive advantage. This interactional framework forms the theoretical foundation for the hypotheses proposed in this study. In this context, the following hypotheses were developed.

H1: Digitalisation in the supply chain significantly affects supply chain innovation.

H2: Supply chain integration significantly affects supply chain innovation.

3.2. Digitalisation and Sustainability

In the contemporary business landscape, industries and companies adopt many creative tactics, particularly digital transformation, to sustain their competitive advantages amid escalating environmental risks. Uncertainty within the supply chain is mainly attributed to knowledge asymmetry and data inadequacy, hindering the capacity to cultivate foresight and execute optimal judgments. Digital technologies like blockchain emerge as strategic instruments capable of mitigating supply chain risks. In a volatile corporate landscape influenced by financial variations, environmental emergencies, and socio-economic changes, supply chain digitalization provides a vital advantage for companies to enhance flexibility, adjust to evolving circumstances, and improve sustainability outcomes (Abourokbah et al., 2023).

Lock & Seele (2017) established a conceptual framework for sustainability stakeholderism in the digital era, employing a normative approach that prioritizes sustainability in stakeholder mapping. The authors categorize digital sustainability stakeholders into three primary groups: big data producers, aggregators, and users, illustrating that digital transformation transcends mere technicality and reconfigures the distribution of responsibilities concerning sustainability objectives. This method underscores the necessity for all stakeholders to converge behind a common vision for the achievement of sustainable transformation.

He et al. (2017) investigated the influence of digital technologies on environmental engagement throughout China's urban transition. They demonstrated that ICT-based governance processes serve as effective instruments to facilitate environmental sustainability for governance actors and citizens. The research indicates that digital participation platforms provide crucial potential for ecological sustainability and social mobilization, particularly in environments characterized by weak social stability and swift economic development.

Stürmer et al. (2017) advanced the discourse on digital sustainability from an information science standpoint, highlighting that digital information is a non-depleting resource that appreciates in value with usage. In their research, they introduced a "base model" for the sustainable preservation of digital information, validated this model through case studies, and comprehensively analyzed the unique characteristics of sustainable digital products. They advocate for the sustainable design of digital ecosystems through the formulation of a multidisciplinary research agenda.

Investigations into the impact of digitalization on enhancing sustainability performance within supply chains yield significant insights. Le et al. (2024) demonstrate that digital supply chain practices exert a direct and substantial beneficial influence on sustainability performance, suggesting that digitalization serves as both a technology advancement and a strategic component that facilitates sustainable growth for enterprises. Sarkis et al. (2021) assert that digital technology can enhance environmental sustainability performance; nevertheless, meticulous and strategic planning is essential to fully actualize this potential.

Kaya & Yıldız (2025) demonstrated that digital transformation has a large and favorable impact on both green production practices and environmental performance within the manufacturing sector. The research indicates that green manufacturing significantly mediates the influence of digital transformation on environmental performance. These findings underscore that digitization must be regarded as both a technological instrument and a strategic governance component in attaining sustainability objectives.

Kayıkçı (2018) demonstrates that digitalization in the logistics sector enhances operational efficiency and directly fosters environmental sustainability. His research has shown that digital logistics systems offer several advantages, including decreased energy usage, diminished carbon emissions, and enhanced resource use efficiency.

Digitalisation is considered a technological tool for achieving sustainability goals and a transformative force that facilitates organisational alignment, stakeholder collaboration and social engagement. In the supply chain context, digitalisation reduces risks and provides flexibility and agility by enhancing information flow in complex and uncertain business environments. Thus, digitalisation gains strategic importance as a critical component of sustainable supply chain management.

In this context, the following hypothesis was developed.

H3: Digitalisation in the supply chain significantly affects the sustainable supply chain.

3.3. Integration and Sustainability

There is a natural and strategic synergy between sustainability and supply chain management. Modern approaches consider sustainability not only as a goal limited to financial indicators such as operational efficiency or profitability, but also as a holistic paradigm that includes dimensions such as social impact, environmental footprint and ethical responsibility. This multidimensional relationship gains importance not only as a theoretical discussion area, but also as an application area with the potential to create social impact. While studies on sustainable supply chains are increasing in the literature, it has become an academic necessity to critically evaluate existing approaches and determine strategic orientations for the future (Winter & Knemeyer , 2013).

The research by Oubrahim et al. (2023) demonstrates the beneficial effect of supply chain integration on sustainable supply chain performance. The research indicates that integration expedites information flow, enhances process harmonization, and fortifies collaboration across supply chain participants. These improvements substantially enhance the effective achievement of sustainability objectives encompassing environmental, social, and economic dimensions.

Chauhan et al. (2022) underscore the strategic significance of Industry 4.0 technology in sustainable supply chain management. The research indicates that the incorporation of technologies like the IoT, big data analytics, cyber-physical systems, and artificial intelligence into supply chain operations presents a substantial opportunity to enhance environmental, economic, and social sustainability outcomes. The real-time data sharing and sophisticated decision support systems offered by these technologies are essential instruments for attaining sustainability objectives.

Kang et al. (2018) similarly discovered that the integration of suppliers and customers strongly influences sustainability management practices. Research indicates that the integration of suppliers and customers enhances the implementation of sustainability policies and positively influences overall sustainability performance. These findings indicate that supply chain integration should be seen as a strategic tool that enhances operational efficiency and fulfils environmental and social goals.

In this context, the following hypothesis was developed.

H4: Supply chain integration significantly affects supply chain sustainability.

3.4. Innovation and Sustainability

The World Commission on Environment and Development (1987) defines sustainability as a developmental approach that seeks to fulfil existing demands without compromising the ability of future generations to satisfy their own needs (Singh & Trivedi, 2016). This strategy anticipates the safeguarding of the environment while concurrently pursuing economic growth and social development objectives in a balanced manner. In the current competitive business landscape, sustainable supply chains provide companies a considerable strategic advantage and underscore the imperative to establish a robust synergy between creative enterprises and supply networks.

The influence of sustainable innovation must extend beyond particular companies and be disseminated throughout the entire supply chain, requiring methodical management. In contemporary economies, competitive advantage derives from the comprehensive efficacy of the entire supply chain rather than the performance of isolated enterprises. Sustainability-focused supply networks are essential for operations and serve as a critical factor for differentiation and long-term value generation (Tebaldi et al., 2018).

Kusi-Sarpong et al. (2019) underscored that innovation management is essential for enhancing sustainability in production-oriented supply chains and showed a substantial and positive correlation between innovation and sustainability. The study indicates that companies should regard innovation capacity as a strategic factor that enhances sustainable practices. Pereira de Carvalho & Barbieri (2012) contend that sustainable supply chain management must extend beyond merely mitigating environmental and social implications; these impacts should be adeptly managed through innovation. Their case study of a Brazilian cosmetics firm demonstrates that incorporating sustainable innovation at all stages of the supply chain mitigates social and environmental repercussions across the entire product life cycle.

Gupta et al. (2020) emphasise that sustainable supply chain innovation should be addressed not only with its technical and economic dimensions, but also with its managerial and cultural dimensions. The study reveals that managing sustainability and innovation with a holistic approach directly affects the capacity of enterprises to create sustainable value. This holistic approach generates environmental benefits and contributes to the sustainable construction of firms' competitive advantage.

In this context, the following hypothesis was developed.
H5: Supply chain innovation significantly affects supply chain sustainability.

4. CONCLUSION, DISCUSSION AND RECOMMENDATIONS

This paper theoretically analyzes the impact of integration, innovation, and digitalization on sustainable supply chain management, elucidating the interrelationship among these three aspects for sustainability performance. In the current dynamic corporate landscape, global rivalry, swiftly evolving consumer expectations, and imperatives of environmental sustainability compel organizations to develop more adaptable, efficient, and innovative supply chains.

The literature study and theoretical evaluations indicate that these three parameters enhance sustainability performance both directly and indirectly. Digitalisation enhances information flow by reinforcing supply chain integration and innovation potential, facilitating real-time data exchange through technologies such as blockchain, artificial intelligence, and the Internet of Things (Le et al., 2024; Seyhan et al., 2021). This enhances operational efficiency and offers benefits in demand forecasting, inventory management, and logistics coordination. Furthermore, digital technologies positively influence sustainability metrics, including waste management, carbon footprint reduction, and resource efficiency (Abourokbah et al., 2023; Sarkis et al., 2021). These results corroborate hypothesis H3.

Integration within the supply chain, encompassing internal, supplier, and customer integration, has been shown to directly influence sustainable performance. Integrated structures promote waste minimization, energy conservation, and circular economy initiatives; supplier integration enhances sustainable supply chain practices, while customer integration bolsters demand-driven production models (Oubrahim et al., 2023; Kang et al., 2018). This corroborates hypothesis H4. Ultimately, innovation has been recognized as a catalyst for sustainable supply networks. Specifically, eco-innovations (e.g., low-carbon production, recycling technologies) and social innovations (e.g., ethical sourcing, fair trade) promote the attainment of environmental and social sustainability objectives (Kusi-Sarpong et al., 2019). This reinforces the validity of hypothesis H5.

This study's findings indicate that integration, innovation, and digitalization mutually enhance each other, contributing to the effectiveness of sustainable supply chain management. The results demonstrate the distinct effects of each component on sustainability and the synergistic advantages resulting from their interconnections.

The role of digitalization in enhancing sustainability performance is gaining prominence in both academic and practical literature. The findings of this study correspond with those of Le et al. (2024) and Seyhan et al. (2021), demonstrating that digital technologies serve not only as instruments for data processing and process monitoring but also as fundamental components of strategic sustainability practices. Specifically, technologies like blockchain, IoT, and artificial intelligence facilitate enhanced management of environmental impacts by augmenting transparency, traceability, and reliability throughout the supply chain (Sarkis et al., 2021; Abourokbah et al., 2023). In this environment, digitalization has emerged as a "transformative force" in sustainable supply chain management.

Nonetheless, the advantages of digitalization do not manifest uniformly across all organization sizes. Small and medium-sized enterprises particularly have challenges, including insufficient funding, inadequate technological infrastructure, and limits in human capital when it comes to accessing, implementing, and adapting digital technologies. This indicates that organizational competencies and supportive policies are essential for properly leveraging the promise of digitalization.

The research further substantiates that supply chain integration is an essential foundation for sustainability. Oubrahim et al. (2023) and Kang et al. (2018) underscore that internal, supplier, and customer integration enhances resource utilization efficiency. It minimizes waste production and loss through comprehensive process management. Supplier integration facilitates the extensive adoption of sustainable material sourcing and low-carbon manufacturing, whereas customer integration mitigates overproduction and surplus inventories by implementing demand-driven production planning. This discovery indicates that sustainability has transitioned from a mere ancillary responsibility to a strategic competitive advantage.

Thirdly, the influence of innovation on sustainability is a well-highlighted topic in the literature. The findings of this study, consistent with Kusi-Sarpong et al. (2019), indicate that sustainable innovation must provide technological solutions while simultaneously being assessed through its social and managerial dimensions. Eco-innovations, such as recycling technologies and energy efficiency solutions, mitigate the environmental effects of companies, whereas social innovations, including fair trade and ethical sourcing, enhance the human-centred sustainability of the supply chain. The dissemination of innovation inside the organization and across the supply chain promotes stakeholder engagement in sustainable practices and fosters collective value generation.

One of the unique contributions of this study is that it provides a holistic theoretical framework that jointly assesses the impact of digitalisation, integration and innovation on sustainable supply chains. In the literature, these elements are generally analysed as independent variables; the relational dynamics between them have been addressed to a limited extent. In this context, the study fills the theoretical gaps and provides guiding results for practitioners.

On the other hand, the theoretical level of the study has some limitations due to the lack of empirical tests. However, this situation also provides a rich starting point for future research. Sector-based comparisons, time series data analyses or structural modelling studies can further strengthen this framework.

Recommendations for Businesses

Digital transformation should be a strategic vision, not just a technological investment.

Integrating technologies such as blockchain, IoT and artificial intelligence into supply chains increases operational efficiency and contributes directly to sustainability goals. However, these technologies require not only hardware or software, but also cultural transformation and competent human resources. Therefore, businesses should consider digital transformation and support it with organisational change management.

A holistic approach to supply chain integration should be adopted.

In addition to internal integration, long-term, transparent and trust-based co-operation with suppliers should be developed; customer feedback should be integrated into product development and planning processes. In particular, customer-oriented demand forecasting systems and supplier innovation partnerships will increase sustainability.

Eco-innovation and social innovation strategies should be integrated into the corporate culture.

Sustainability-oriented innovations such as low-carbon production, recycling, ethical procurement, and inclusive business models should be aligned with the corporate strategy by spreading not only to R&D departments but also to the entire organisation.

Sectoral collaborations and digital clusters should be encouraged for SMEs.

Joint use of digital infrastructures, technology sharing and data integration within the supply chain can create cost advantages for small and medium-sized companies that lack resources.

Recommendations for Policy Makers and Public Institutions

Digital transformation support for SMEs should be increased.

State-supported incentive programmes should include multi-dimensional support such as financing technology investments, digital literacy training, and sustainability consultancy. In addition, establishing "digital transformation guidance centres" can facilitate the transformation processes of SMEs.

Sustainable supply chain standards and certification systems should be popularised.

National regulations on issues such as green procurement, ethical production and carbon footprinting should be developed, and the compliance of supply chain actors with these standards should be encouraged.

Provide infrastructure for data sharing and platform economies.

Establish secure, anonymised and regulated national digital supply chain platforms enabling digital data sharing between firms. In this way, firms can be more effective in data-based decision-making processes.

Sustainability incentives should be made technology and innovation-oriented.

Environmental incentives should be restructured specifically for sustainability strategies such as eco-innovation, clean technology investments and innovative waste management practices.

Suggestions for Academics and Future Research

The interactions between digitalisation, integration and innovation should be modelled empirically.

The theoretical framework of this study can be tested with multivariate analyses (e.g. structural equation modelling), and causal relationships between variables can be revealed more clearly.

Sectoral and regional comparative studies should be conducted.

The effects of digitalisation and integration on sustainability may differ in different sectors (e.g. automotive, textile, food) and geographies. In this context, conducting more specific field studies will

increase the generalisability of the findings.
Interdisciplinary models for sustainable digital supply chains should be proposed.
Integrated theoretical models that combine engineering, business, environmental sciences and information systems would contribute to the theoretical and applied literature.
Qualitative research focusing on social and managerial dimensions is needed.
The role of human factors such as leadership, culture, employee resilience and ethics in sustainable innovation and digital transformation processes should be further investigated.
As a result of the research, the following model is proposed for researchers.

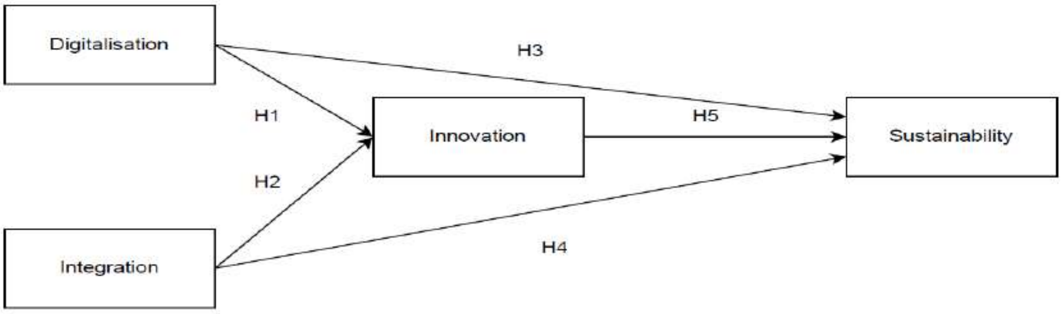

Figure 1: Proposed Model

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ARTIFICIAL INTELLIGENCE IN PURCHASING PROCESSES IN LOGISTICS

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Abstract

Artificial Intelligence (AI) is revolutionizing the logistics industry, particularly in purchasing and procurement operations. Traditionally, purchasing in logistics has been characterized by manual tasks, subjective decision-making, and limited data utilization. AI integration enables organizations to streamline procurement workflows, minimize operational costs, improve supplier performance, and make data-driven decisions with greater precision.

AI technologies such as machine learning, natural language processing, and predictive analytics are being implemented to enhance various aspects of purchasing. These technologies allow for the analysis of large datasets to forecast demand, automate repetitive tasks, and evaluate supplier performance based on historical data and real-time indicators. Real-time price comparisons, dynamic sourcing strategies, and advanced risk assessments become possible, enabling more agile responses to market fluctuations and supply chain disruptions. Key benefits of AI in logistics purchasing include enhanced inventory forecasting accuracy, shorter procurement cycle times, and improved supplier negotiations driven by predictive insights. AI systems support proactive decision-making by identifying patterns and trends that are not easily detectable through conventional methods. Industry case studies demonstrate tangible improvements in procurement efficiency, cost savings, and supply chain resilience through AI implementation.

Despite its advantages, AI adoption in purchasing also introduces challenges, including the complexity of system integration, data quality concerns, and the need for employee reskilling. Successfully leveraging AI requires a robust digital infrastructure, clear strategic alignment, and continuous organizational adaptation.

The integration of AI into purchasing functions represents a strategic shift toward smarter, more responsive supply chains. Companies adopting AI-enhanced procurement processes are better positioned to navigate uncertainty, increase operational transparency, and maintain a competitive edge in a rapidly evolving logistics landscape.

Keywords: Artificial Intelligence, Procurement Automation, Smart Purchasing, Supply Chain Optimization, Predictive Analytics in Logistics

INTRODUCTION

In recent years, the integration of Artificial Intelligence (AI) into logistics has emerged as a transformative force, particularly within the domain of purchasing processes. As global supply chains grow increasingly complex and demand greater efficiency, AI offers innovative solutions to streamline procurement activities, enhance decision-making, and improve overall supply chain performance. Through the application of machine learning algorithms, predictive analytics, and intelligent automation, AI facilitates more accurate demand forecasting, dynamic pricing, optimized inventory management, and strategic supplier selection. These capabilities enable organizations to reduce procurement lead times, lower operational costs, and increase responsiveness to market fluctuations. Moreover, AI-driven systems can process vast volumes of data in real time, allowing for continuous improvement and adaptation within purchasing functions. As such, the incorporation of AI into purchasing processes is not merely a technological upgrade, but a strategic shift that holds significant implications for the efficiency, agility, and resilience of modern logistics operations.

The United Nations established the Sustainable Development Goals (SDGs), a framework of global development goals, in 2015, with the aim of achieving a better and sustainable future by 2030. It covers a total of 17 goals in three main areas: social, economic, and environmental. According to the Sustainable Development Goals Report 2024, only 17% of the SDGs are on track, nearly half are making little or average progress, and more than a third are stagnating or even regressing. In modern business, optimizing supply chains is essential for a company's success and growth (Annosi, M.C.; Brunetta, F.; Bimbo, F.; Kostoula, M., 2021). Logistics and supply chain networks are key drivers of economic and social development at the national level. In order to measure logistics efficiency and performance across countries, the World Bank publishes the Logistics Performance Index (LPI). A country's logistics environment, policies, and investments affect logistics efficiency, which is an important indicator of international trade and economic progress. The optimization of logistics becomes an important element of achieving sustainability (Matantseva, O.Y.; Spirin, I.; Ulitskaya, N.; Kazantsev, I., 2021). It is possible for AI to transform supply chain management in a number of ways, including improving forecasting, optimizing transport routes, and managing inventory in a more efficient manner that reduces emissions and resource consumption. In addition to enhancing efficiency, this can minimize the environmental impact of logistics operations by reducing costs. AI in logistics could enable sustainability and fundamentally change the way supply chains are managed and their environmental impact, not just in the short term, but in the long run as well (Benzidia, S.; Makaoui, N.; Bentahar, O, 2021).

In the intersecting fields of Artificial Intelligence and sustainable logistics, the number of academic articles published each year consistently increases. Using databases like Google Scholar or Elsevier Scopus, it can be observed that the number of articles mentioning "artificial intelligence" and "logistics" has increased significantly over recent years.

Figure 1. Number of publications related to AI and logistics between 2015 and 2023.

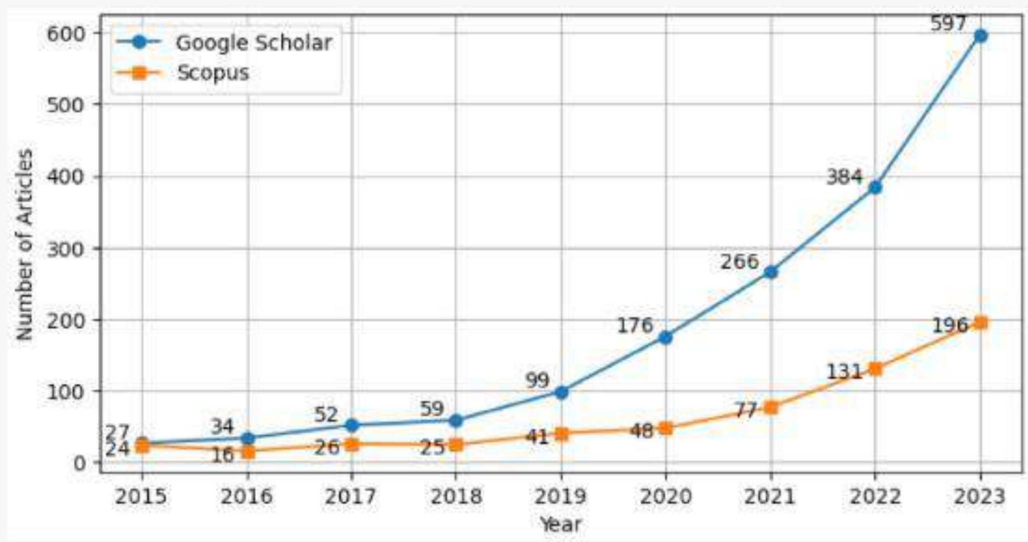


Figure 1. Number of publications related to AI and logistics between 2015 and 2023 (Sustainability 2024)

When compared to less advanced competitors, organizations that have implemented AI in supply chain management have seen significant savings, as they were able to reduce logistics expenses by 15%, decrease stock levels by 35%, and increase service efficiency by 65% (Alicke, K.; Knut, D.; Görner, S.; Mori, L.; Rebuffel, P.; Reiter, S.; Samek, R., 2021).

Methodology

The methodology of integrating Artificial Intelligence (AI) into purchasing processes within logistics is built on a rigorous, multi-stage framework that bridges data analytics, machine learning, decision science, and procurement management to transform procurement into an intelligent, adaptive system. The approach begins with defining the procurement problem—for example, misaligned supplier selection, cost volatility, or inefficiencies in order processing—establishing clear research objectives guided by a combination of literature and industry insight (Guida, Moretto, & Caniato, 2023). This stage is followed by data collection and preprocessing, drawing on structured internal sources such as ERP, TMS, and WMS systems, as well as unstructured data from supplier documents, performance records, and relevant external market indicators, aligning with the comprehensive data-driven perspective emphasized in surveys of AI applications in supply chain management (Daios et al., 2025). Data cleaning, normalization, and feature engineering are applied to generate meaningful inputs—like supplier reliability scores or cost-efficiency indicators—necessary for modeling. Next, model development employs predictive analytics techniques, including machine learning models like random forests, gradient boosting, neural networks, and time-series methods like ARIMA or LSTM, to forecast demand, lead times, or price fluctuations (Culot, Podrecca & Nassimbeni, 2024). For optimizing supplier selection, AI-driven multi-criteria decision analysis (MCDA) frameworks—such as AI-augmented AHP, TOPSIS, or fuzzy decision systems—are leveraged to consider both quantitative (cost, delivery, performance) and qualitative (sustainability, risk) criteria (Zhang & others, preprint; Fosso's informed AI models). Techniques such as reinforcement learning or genetic algorithms may be incorporated to optimize order allocation and safety stock under dynamic supply chain conditions (Kosasih & Brintrup, 2021). Concurrently, automation via Robotic Process Automation (RPA) integrated with AI is used to streamline repetitive procurement tasks like purchase order creation, invoice matching, and contract approvals, freeing human decision-makers to focus on more strategic issues (Jones, 2025). After models are developed, they undergo validation and testing using both technical metrics (e.g., precision, recall, MSE) and managerial outcomes (e.g., cost reduction, lead-time improvement), as echoed in applied predictive analytics for supply chain optimization (Iseri et al., 2025). The validated models are then deployed into operational procurement and logistics systems, supporting real-time or near-real-time decision making. A continuous monitoring and refinement phase ensures adaptability, drawing on new data to improve robustness, and aligning with findings on AI's role in building resilient, human-centric supply chains (Daios et al., 2025) MDPI. Finally, throughout all stages, ethical, organizational, and managerial considerations are critical—these include ensuring data privacy, addressing algorithmic bias, establishing governance frameworks, and managing the people's side of AI adoption through training and change management (Guida et al., 2023; Jones, 2025). This integrated methodology transforms traditional procurement processes in logistics into data-driven, intelligent systems, enhancing efficiency, resilience, and sustainability in line with emerging Industry 4.0 and supply chain digitalization trends.

Analysis

The integration of Artificial Intelligence (AI) into purchasing processes within logistics has introduced a paradigm shift in how procurement functions are conceptualized and executed. At the core of this transformation is AI’s capacity to process and analyze large volumes of structured and unstructured data in real time, allowing for data-driven decision-making that far exceeds human capabilities in both speed and accuracy.

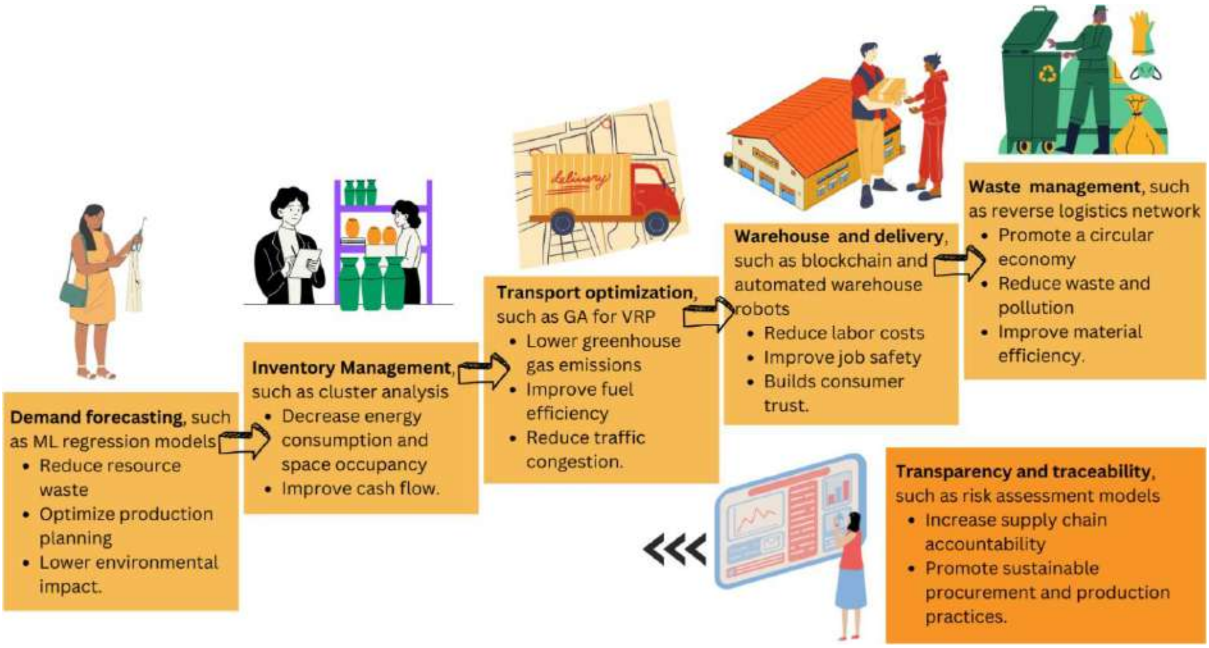
One of the most significant impacts of AI in purchasing is in the area of **demand forecasting**. Traditional forecasting methods often rely on historical data and static models, which may not account for sudden market changes or emerging trends. In contrast, AI-driven models utilize machine learning algorithms that continuously learn from new data inputs—including market signals, customer behavior, and external factors such as geopolitical events or weather patterns—to produce dynamic and adaptive forecasts. This leads to more precise procurement planning, minimizing stockouts and reducing excess inventory, which directly translates to cost savings and improved service levels.

Another critical function enhanced by AI is **supplier evaluation and selection**. AI tools can assess suppliers not only on cost and delivery metrics but also on qualitative factors such as reliability, sustainability practices, and risk exposure. Natural language processing (NLP) algorithms can scan financial reports, news articles, and compliance databases to evaluate supplier credibility in ways that would be labor-intensive and time-consuming for human analysts. Furthermore, AI can support **supplier relationship management** by identifying performance trends and proactively flagging potential issues, thus fostering more resilient and transparent supply chains.

AI also contributes significantly to the **automation of routine procurement tasks**. Processes such as purchase order generation, invoice matching, and contract management can be executed with minimal human intervention through robotic process automation (RPA) integrated with AI. This not only increases operational efficiency but also reduces the likelihood of human error and frees up procurement professionals to focus on more strategic initiatives.

However, the deployment of AI in purchasing is not without challenges. **Data quality and availability** remain major concerns, as AI systems require large, clean datasets to function effectively. Inconsistent or siloed data can compromise the accuracy of AI outputs. Additionally, **organizational resistance** and lack of skilled personnel to manage and interpret AI tools can hinder successful implementation. Ethical considerations, particularly around data privacy and algorithmic transparency, must also be addressed to ensure responsible use of AI technologies.

Overall, the analysis reveals that while AI holds immense potential to revolutionize purchasing processes in logistics, its success depends on careful implementation, appropriate data governance, and the upskilling of the workforce. Companies that are able to integrate AI effectively will likely gain a significant competitive advantage in the increasingly complex and fast-paced global supply chain environment.



(AI in sustainable logistics)

The analysis phase in AI-driven purchasing processes within logistics involves systematically transforming processed data and model outputs into actionable insights that enhance procurement decision-making, supplier management, and overall supply chain performance. After data preprocessing and model development, the collected information is subjected to advanced analytical techniques to uncover patterns, trends, and anomalies in purchasing behavior, supplier performance, inventory levels, and cost fluctuations. Predictive models generate forecasts for demand, lead times, and price volatility, which are then analyzed to identify potential risks, procurement bottlenecks, and opportunities for cost optimization (Guida, Moretto, & Caniato, 2023). Multi-criteria decision-making analyses, often AI-augmented, allow organizations to evaluate and rank suppliers based on quantitative metrics such as cost, delivery speed, and defect rates, alongside qualitative criteria including sustainability performance, compliance, and strategic alignment (Culot, Podrecca, & Nassimbeni, 2024). Optimization algorithms, including reinforcement learning and genetic algorithms, provide analytical insights into order allocation, inventory replenishment, and transportation routing, enabling the selection of the most efficient and resilient procurement strategies under dynamic market conditions (Kosasih & Brintrup, 2021). Additionally, natural language processing (NLP) is applied to unstructured data such as supplier reports, contracts, and external market news, generating insights on emerging risks, market trends, or supplier reliability that would otherwise remain hidden. The analysis is iterative, incorporating continuous monitoring and feedback loops to refine predictive accuracy and ensure decision relevance, thereby creating an adaptive system that supports both short-term operational choices and long-term strategic planning. This analytical framework not only facilitates evidence-based decision-making but also enhances transparency, accountability, and risk mitigation in logistics purchasing processes, aligning with contemporary objectives in Industry 4.0 and digital supply chain management (Daios et al., 2025; Iseri et al., 2025).

Current and Future Trends in AI-Driven Logistics Optimization

The current and emerging trends in AI-driven logistics optimization reflect a significant transformation in supply chain management, driven by advanced analytics, automation, and intelligent decision-making tools. Presently, logistics organizations are leveraging predictive analytics and machine learning algorithms to improve demand forecasting, inventory management, and order fulfillment, using historical data, market indicators, and real-time operational metrics to minimize stockouts, reduce overstock, and optimize delivery schedules (Guida, Moretto, & Caniato, 2023; Daios et al., 2025). Autonomous systems, including automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and drones, are increasingly integrated into warehousing and transportation operations, streamlining repetitive tasks, reducing human error, and enhancing operational efficiency (Culot, Podrecca, & Nassimbeni, 2024). Real-time visibility platforms, supported by AI-enhanced asset tracking and predictive alerts, allow logistics managers to proactively respond to disruptions, optimize routing, and improve customer service levels. AI-powered control towers aggregate and analyze data across the supply chain, enabling holistic decision-making, risk mitigation, and scenario planning. Looking ahead, emerging trends point to the convergence of AI with spatial intelligence, augmented reality (AR), and hyperautomation to further optimize logistics operations, allowing machines to navigate complex physical environments and execute end-to-end automated processes with minimal human intervention (Kosasih & Brintrup, 2021; Jones, 2025). Sustainability is becoming a key driver of AI applications, with algorithms optimizing routes, fuel usage, and energy consumption to reduce emissions and meet environmental compliance standards. Moreover, the integration of AI with blockchain technologies is expected to enhance transparency, traceability, and trust across the supply chain, providing tamper-proof records and ensuring secure, real-time shipment tracking. Collectively, these trends indicate that AI is not only improving efficiency and cost-effectiveness in logistics but also enabling more resilient, adaptive, and environmentally responsible supply chains, laying the foundation for the next generation of digital logistics management (Iseri et al., 2025; Daios et al., 2025).

Conclusion

In conclusion, the integration of Artificial Intelligence into purchasing processes and logistics represents a paradigm shift in supply chain management, enabling organizations to achieve unprecedented levels of efficiency, accuracy, and adaptability. The methodological framework emphasizes data-driven decision-making, combining predictive analytics, optimization algorithms, multi-criteria supplier evaluation, and automation to streamline procurement and reduce operational inefficiencies. Analytical processes convert complex datasets into actionable insights, supporting evidence-based decision-making, risk mitigation, and strategic planning. Current trends, including autonomous systems, real-time visibility platforms, AI-powered control towers, and predictive demand forecasting, demonstrate tangible improvements in operational performance, while emerging trends such as hyperautomation, spatial intelligence, augmented reality, AI-driven sustainability initiatives, and blockchain integration indicate a future of increasingly resilient, transparent, and environmentally responsible supply chains. Collectively, these developments underscore that AI is not merely a tool for operational improvement but a strategic enabler, transforming logistics and purchasing processes into intelligent, adaptive systems capable of responding to dynamic market conditions and evolving business requirements. As organizations continue to adopt and refine these technologies, AI-driven logistics optimization is poised to become a critical competitive differentiator, ensuring efficiency, sustainability, and long-term resilience across global supply chains.

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AN ANALYSIS OF WOMEN'S EMPLOYMENT IN LOGISTICS: EVIDENCE FROM TÜRKİYE

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ABSTRACT:
This study aims to analyze the current state of women's employment in logistics, compare key trends, and provide future projections for the logistics industry in Türkiye using Household Labor Force Survey microdata from 2004 to 2021. We use logit regression analysis to examine the factors influencing the likelihood of employment in the logistics sector by gender. Additionally, we assess the factors affecting women's chances of reaching managerial positions within the sector, controlling for variables such as education, age, marital status, and region. The study shows women are underrepresented in logistics, especially in managerial roles. For females, secondary and upper education level graduates are more likely to work in the logistics sector. On the other hand, for males, the sector mainly attracts those with low or medium levels of education. In addition, our results also show that higher education levels increase the chances of managerial positions for females. Regionally, areas with more developed logistics infrastructure and larger urban centers, such as Istanbul, offer greater opportunities for both men and women, particularly for women with higher educational achievements. However, among those with higher education, women are more likely than men to hold managerial positions in logistics than in other industries. The findings highlight the importance of gender-sensitive policies and targeted initiatives to overcome these barriers.

KEYWORDS
Employment, Logit Regression, Logistics, Women

RELATED TOPICS
Logistics Management, Special Topics in Logistics

GENERATIVE AI FOR SUSTAINABLE LOGISTICS DECISION-MAKING: A MULTI-LEVEL FRAMEWORK INTEGRATING HUMAN-AI COLLABORATION

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ABSTRACT:
Purpose:
This study aims to develop a conceptual framework that explains how generative artificial intelligence (AI) can support sustainable logistics decision-making across strategic, tactical, and operational levels. By integrating theories of human-AI collaboration and multi-level supply chain governance, the paper explores how generative AI can enhance, complement, or co-create decisions that align with environmental, social, and economic goals.
Study design/methodology/approach:
A theory-driven conceptual research design is adopted. The framework is constructed by synthesizing literature from sustainable logistics, generative AI, and organizational decision-making. The proposed model maps the roles of generative AI in different levels of decision-making and outlines possible collaboration modes between human experts and AI agents. Illustrative use cases are provided to demonstrate practical applicability.
Findings:
The paper proposes a multi-level framework in which generative AI serves distinct functions: strategic foresight and scenario creation at the strategic level, optimization and planning at the tactical level, and real-time support at the operational level. Three forms of human-AI interaction—advisory, co-creative, and delegated—are introduced, highlighting key enablers such as trust, explainability, and organizational readiness. The study underscores the importance of aligning AI capabilities with decision complexity and sustainability impact.
Originality/value:
This is one of the first papers to systematically explore the intersection of generative AI, sustainable logistics, and multi-level decision-making. By articulating distinct collaboration modes and decision contexts, the paper contributes to both theory development and practical guidance in an emerging field of strategic importance.
KEYWORDS
Augmented Rationality, Decision-Making, Generative AI, Human-AI Collaboration, Multi-Level Framework, Sustainable Logistics

RELATED TOPICS
Artificial Intelligence in logistics and supply chains, Sustainability in logistics and supply chains

ASSESSING FACTORS INFLUENCING HOUSEHOLD MEDICATION WASTE IN A CIRCULAR ECONOMY FRAMEWORK

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ABSTRACT:
Purpose:
Household medication poses environmental and public health risks like accidental poisoning, antimicrobial resistance, and resource contamination. This study aims to identify key factors that influence how households store, dispose of, and reuse medications. It aims to provide policy recommendations for better pharmaceutical waste management, framing these challenges within circular economy principles and emphasizing sustainability.
Study design/methodology/approach:
A mixed-method approach was implemented, involving surveys administered to 401 household members and 43 pharmacists in İzmir, Türkiye. Quantitative data were analyzed using logistic regression, while qualitative insights were obtained through interviews. The study explored sociodemographic influences, awareness levels, pharmacist practices, and attitudes toward reuse.
Findings:
Medication management behaviors vary according to individual characteristics and access to information, with inappropriate disposal via household waste remaining widespread among those without proper guidance. Overall, public awareness of safe disposal methods remains limited across demographic groups. Pharmacists generally endorse responsible disposal and reuse practices but face legal, ethical, and logistical barriers. While public willingness to reuse medicines exists under certain conditions, persistent concerns about product integrity and trust highlight the need for clearer frameworks and safety assurances.
Originality/value:
This study provides a comprehensive perspective by analyzing household and pharmacist behaviors within a single framework. By aligning medication waste management with circular economy principles, the study contributes to ongoing efforts to build more sustainable and resilient healthcare practices. The results emphasize the necessity for collaborative policy action, enhanced pharmaceutical return systems, and focused awareness campaigns to minimize waste and encourage safe reuse practices.

KEYWORDS
Circular Economy, Household Medication Waste, Medicine Reuse, Pharmacists, Waste Management

RELATED TOPICS
Healthcare Logistics and Supply Chains, Sustainability in Logistics and Supply Chains

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COGNITIVE LOAD AND LEGAL RESPONSIBILITY IN SMART MARITIME LOGISTICS: THE HUMAN FACTOR UNDER PRESSURE

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ABSTRACT:
Purpose:
Smart logistics technologies, such as AI-assisted decision systems and IoT-based cargo monitoring systems, are increasingly integrated into maritime operations, as they are becoming the new normal among maritime operations. While these systems aim to minimise human error and optimise performance as they focus on accuracy and efficiency, they also simultaneously impose new psychological burdens on seafarers and logistics personnel. The expectation to override, monitor, or validate machine outputs creates a high-stress environment where the boundaries of legal responsibility become blurred.
Study design/methodology/approach:
This study explores how increasing cognitive load in smart maritime logistics environments affects human decision-making and legal responsibility. While automation enhances operational efficiency, it also brings new forms of psychological pressure, expecting seafarers to stay alert, make judgment calls, and be accountable even when working alongside AI systems. Drawing from maritime law, psychology, and business administration, this paper argues that current legal frameworks fall behind these technological changes. Emotional fatigue, decision-making stress, and mental workload are rarely considered in liability assessments. Using a qualitative, interdisciplinary approach, the research combines legal analysis with human factors literature, supported by case studies and references to the Turkish Commercial Code, MLC 2006, and IMO instruments.
Findings:
Ultimately, the analysis highlights that legal frameworks governing maritime logistics must evolve with technological advancements by addressing structural risks introduced by automation and acknowledging the psychological vulnerabilities of the human element.
Originality/value:
The paper's originality lies in framing psychological vulnerability not as individual weakness, but as a systemic blind spot in maritime law, calling for a more human-centred understanding of legal responsibility in an era increasingly shaped by automation.

KEYWORDS
Smart Logistics, Cognitive Load, Human Factor, Liability in AI Systems, Human-Centred Regulation, Maritime Labour Law.

RELATED TOPICS
Artificial Intelligence in logistics and supply chains, Transportation and logistics law, Humanitarian logistics and supply chains.

ARTIFICIAL INTELLIGENCE-DRIVEN DECISION SYSTEMS IN THE TRANSFORMATION OF DISTRIBUTION PROCESSES: REDEFINING SUSTAINABILITY AND LOGISTICS PERFORMANCE WITHIN MULTI-CHANNEL MARKETING STRATEGIES

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ABSTRACT:
Artificial intelligence-based decision support systems are powered by technologies such as machine learning, and natural language processing in logistics and distribution processes, enabling autonomous complex decisions. Digitalization in logistics is shaped by the smartening of distribution centers, unmanned delivery technologies, multi-channel integration and sustainable transportation. Multi-channel marketing is a strategic approach that aims to provide consumers with a consistent experience across different touchpoints such as applications, social media and callcenters. Sustainability is not only considered environmentally; it is also integrated with economic efficiency, social responsibility and corporate ethics. In this context, sustainable distribution includes applications such as carbon emission reduction, green transportation, reverse logistics, and energy efficiency. Logistics performance is evaluated with multi-dimensional criteria such as speed, cost and customer satisfaction. In this study, it is analyzed how artificial intelligence-supported decision systems, combined with multi-channel marketing strategies, transform distribution processes and contribute to sustainability. While digitalization and changing customer expectations reveal the inadequacy of traditional distribution structures, artificial intelligence technologies allow logistics performance to be redefined. In a multiple case study conducted in three selected businesses from the retail and e-commerce sectors in Türkiye, the effects of artificial intelligence algorithms used in decision-making processes on efficiency and environmental sustainability were evaluated. The findings obtained with the mixed method revealed that artificial intelligence optimizes not only operational success but also green logistics, cost reduction and customer satisfaction. The study emphasizes that the integration of data-driven distribution management with strategic marketing provides competitive advantage.

KEYWORDS
Artificial Intelligence-Driven Logistics, Omnichannel Distribution Strategies, Sustainable Supply Chain Management, Data-Driven Decision Systems, Logistics Performance Optimization

USE OF UNMANNED SURFACE VEHICLES IN COMMERCIAL PORTS

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ABSTRACT:
Purpose:
More than 90% of the world's trade volume is transported by sea. In this transportation mode, ports serve as an important interface between the ocean and the hinterland, enabling the efficient flow of information and goods. First developed for military use, unmanned surface vehicles have significant potential to improve navigational safety by AI-controlled ship traffic and monitoring fishing activities within the ports for civilian use. Additionally, unmanned surface vehicles with night vision capabilities have the potential to fight smuggling activities around commercial ports. For infrastructure inspection, unmanned surface vehicles can be used to detect corrosion, and damage in port structures such as quays, and breakwaters. These vehicles play a crucial role in detecting marine pollution, as well as in regular monitoring of water quality, salinity and temperature. In this context, this study aims to investigate the potential application areas of unmanned maritime vehicles in commercial ports.
Study design/methodology/approach:
The enablers of unmanned maritime vehicle use in commercial ports will be identified and validated through a literature review and expert panels. Following, the criteria will be weighed by employing an appropriate Multi-Criteria Decision-Making method.
Findings:
The primary findings of the study will be sets of criteria in different categories (e.g., safety, security, environment, maintenance) that enable the use of unmanned maritime vehicles in commercial ports.
Originality/value:
Owing to the novelty of the subject, the study is expected to contribute significantly to academic literature and industrial practice.

KEYWORDS
Container Terminals, Maritime Transportation, Maritime Security, Port Monitoring and Surveillance, Unmanned Surface Vehicles

RELATED TOPICS
Autonomous vehicles in logistics and supply chains, Innovative and smart technologies in logistics and supply chains, Terminal management

VALUE STREAM MAPPING AND ORGANIZATIONAL ALIGNMENT IN DIGITAL PROCESS TRANSFORMATION: AN INTEGRATED APPROACH FROM MIS PERSPECTİVE

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ABSTRACT:
Purpose:
While digital transformation and restructuring of technical processes offer significant opportunities to enhance organizational efficiency, overlooking the human factor in these processes seriously threatens the sustainability of success. In this context, the aim of this study is to propose a conceptual framework by integrating the widely used Value Stream Mapping (VSM) technique in digital transformation processes with the perspective of Management Information Systems (MIS) and organizational alignment.
Study design/methodology/approach:
A fictional scenario from the logistics sector is used to explore how technical process design functions within the organizational reality. The study emphasizes, through a scenario-based case study and literature review, that transformation is not solely process-oriented but can be sustainable only through the integration of systems and people. An "As-Is" process map is developed using VSM, a MIS-supported "To-Be" process is proposed, and organizational resistance points are analyzed particularly through Kotter’s change management model and the ADKAR (Awareness-Desire-Knowledge-Ability-Reinforcement) approach.
Findings:
Barriers encountered by individuals during the system transformation process are structurally examined. The results reveal that in digital transformation processes, it is not only the process but also the balance between people and systems that must be managed together.
Originality/value:
The integration of organizational alignment, the informatics support of MIS, and the technical strength of VSM is proposed as a critical triad for successful digitalization.

KEYWORDS
Value Stream Mapping, Digital process transformation, Management Information Systems, Organizational resistance, Change management.

RELATED TOPICS
Innovative and smart technologies in logistics and supply chains Innovation and technology management

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ENHANCING PROCUREMENT DECISION-MAKING THROUGH GENERATIVE ARTIFICAL INTELLIGENCE: AN INTEGRATED SWARA-MAIRCA FRAMEWORK FOR GENAI TOOL EVALUATION

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ABSTRACT:
The rapid advancement of generative artificial intelligence (GenAI) offers considerable potential for enhancing procurement processes, particularly by improving decision-making quality, operational efficiency, and risk man-agement. Nevertheless, the increasing number and functional diversity of GenAI tools create challenges for organizations attempting to identify solu-tions aligned with their strategic and operational needs. To overcome this challenge, the present study proposes an integrated multi-criteria decision-making framework that systematically supports the evaluation and selection of GenAI tools in procurement settings. The model is designed to balance methodological rigor with practical applicability, ensuring its relevance for real-world acquisition environments. The proposed framework is empirically validated through a procurement-based case study. By integrating analytical precision with practitioner-oriented insights, the study provides guidance for organizations managing GenAI-driven procurement decisions in an increas-ingly complex digital landscape.
KEYWORDS
Generative Artificial Intelligence, Procurement Management, Multi-Criteria Decision-Making, SWARA, MAIRCA, Technology Selection
RELATED TOPICS
Application Selection, Decision-Making, Generative AI, Procurement, SWARA, MAIRCA.

SHARING ECONOMY AND MOBILE LOGISTICS: PERFORMANCE ANALYSIS OF CARAVAN RENTAL PLATFORMS

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ABSTRACT:
Purpose:
The aim of this study is to evaluate the performance of digital caravan rental platforms within the framework of the sharing economy and mobile logistics.
Study design/methodology/approach:
This study adopts a multi-criteria decision-making (MCDM) approach to evaluate the performance of digital caravan rental platforms operating within the sharing economy and mobile logistics domains. The methodological design is organized into four main stages. In the first phase, experts, criteria, and alternative digital caravan rental platforms are identified. Following this, the importance levels of experts are determined using neutrosophic sets, while the relative importance of performance criteria is determined through the intuitionistic fuzzy weighted averaging (IFWA) approach. In the third phase, the alternative ranking order method accounting for two-step normalization (AROMAN), built upon intuitionistic fuzzy logic, to rank the platforms based on their performance. Lastly, the results are supported by sensitivity analysis scenarios.
Findings:
The analysis is still in progress; comprehensive findings will be included in the full manuscript submission.
Originality/value:
Although the existing literature offers substantial insights into shared mobility systems and digital platform logistics, there is a noticeable gap concerning the performance evaluation of caravan rental platforms operating within the intersection of the sharing economy and mobile logistics.

KEYWORDS
Caravan Rental Platforms, IF AROMAN, Mobile Logistics, Sharing Economy
RELATED TOPICS
Service supply chains, Innovative and smart technologies in logistics and supply chains

CURRENT SUPPLY CHAIN MANAGEMENT PRACTICES AND CHALLENGES FROM THE PERSPECTIVE OF SUPPLY CHAIN MANAGERS, 2025 - AN EVALUATION IN TÜRKİYE

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ABSTRACT:
Purpose:
To understand supply chain management capabilities, vulnarabilities and recent challenges of companies in Türkiye.
Study design/methodology/approach:
The research was conducted through face-to-face interviews in the light of open-ended and closed-ended questions.
Findings:
The study covers 20 medium and large-sized exporting manufacturing companies in Turkey. Results show that while 40% of them have a basic supplier evaluation system, 60% have a structured and systematic supplier evaluation process. Firms consider themselves to have a good level of supply chain management at level 4 on a 5-point Likert scale. However, they rate their first-tier supplier's quality in terms of organizational capability as 3,2.
80% of them stated that the supply system has become more complex nowadays. The major reasons are logistical/supply chain disruptions and geopolitical issues, longer or alternative route change needs, and global disruptions-like port congestion, can suddenly extend their lead times. All of them cause longer lead times. On the contrary, customers and manufacturers require increasingly faster delivery of products.
They instantly try to improve their supplier pool. Supply chain managers stated that better change management skill is more needed due to high change rapid with 4,2 points.
Originality/value:
The research was executed in 2025 and has up-to-date information. Will contribute to the understanding of management needs, practices, and developing new scientific methodologies or models for future supply chain management approaches..

KEYWORDS
supply chain management capability, vulnarabilities, emerging challenges, supply chain management perspective of executers

RELATED TOPICS
resilient logistics and supply chains, risk management, special topics in logistics and supply chains

SOCIO-ECONOMIC IMPACT ANALYSIS OF DIGITAL TRANSFORMATION IN THE LOGISTICS SECTOR

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ABSTRACT:
Purpose:
Digital transformation is creating significant and fundamental changes in the logistics sector, as in many other sectors. However, the socio-economic impacts of these transformations remain unclear. This study aims to analyze the socio-economic impacts of digital transformation in the logistics sector. The study examines the impact of technologies such as autonomous vehicles, automated storage and retrieval systems (AS-RS), artificial intelligence-based planning, and data analytics, particularly on blue-collar workers, in terms of employment, income, skill requirements, and living standards. By simultaneously examining the risks and opportunities that digitalization may pose at the societal level, the study aims to develop constructive recommendations for policymakers and industry stakeholders.
Study design/methodology/approach:
The study began with a comprehensive literature review on the sectoral impacts of digitalization, followed by field research at logistics companies operating in Turkey. In this context, quantitative and qualitative data were collected through surveys and semi-structured interviews, particularly with blue-collar workers in the logistics sector. The findings were analyzed and evaluated using statistical methods.
Findings:
The proliferation of digital technologies has seen job descriptions shift in some sectors, putting low-skilled workforces at risk. However, the social impacts of digital transformation appear to be mitigated through the implementation of reskilling programs.
Originality/value:
This study will contribute to filling the gap in the literature by focusing not only on the operational but also on the socio-economic impacts of digital transformation. It also offers original analysis and recommendations on how blue-collar workers can be integrated into the digital transformation process.

KEYWORDS
Digital Transformation, Socio-Economic Impact, Blue-Collar Workers, Workforce Transformation

RELATED TOPICS
List about two (maximum of four), topics from the congress topics list, in order of relevance, separated by commas.

ETA ESTIMATION WITH DIGITAL TECHNOLOGIES TO ENSURE VISIBILITY IN LOGISTICS AND SUPPLY CHAINS: A CASE STUDY

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ABSTRACT:

Purpose:

Visibility in logistics is a critical process in terms of customer satisfaction, competitiveness, and cost management. Today, companies have begun to place greater importance on the issue of visibility. The purpose of this study is to provide guidance on how visibility can be achieved in logistics, which technologies are used, and what practices are implemented in real-world applications. Also, one of aims of this study to explore how digital technologies can improve the estimation of Estimated Time of Arrival (ETA) in logistics and supply chains. Enhanced ETA predictions are critical for increasing operational efficiency, minimizing delays, and improving overall visibility across the supply network.

Study design/methodology/approach:

The research is based on a real-life case study involving a leading logistics company implementing advanced digital tools, including some technologic infrastructures such as; GPS tracking, IoT sensors, and machine learning algorithms. Data was collected from transportation logs, systems in use, and delivery records. A predictive ETA model was integrated into the company's logistics platform. The study uses operational processes and evaluations of ETA prediction accuracy before and after developments.

Findings:

The process flows indicate that integrating digital ETA estimation tools significantly improves the accuracy of arrival predictions, reducing deviations. It also enhances coordination between stakeholders, supports proactive decision-making, and reduces customer complaints linked to delivery uncertainties.

Originality/value:

This study contributes to the growing body of research on digital transformation in supply chain management by providing practical insights into the implementation and benefits of real-time ETA prediction tools. It offers an original replicable framework for logistics and supply chain companies aiming to improve visibility, transparency, and responsiveness through digital innovation. The value of this study lie in the fact that there is not enough research study on this topic and area. This study is aims to be a useful resource for those who want to work in this field and us for upcoming research study.

KEYWORDS

Digitalization at transportation, Estimated time of arrival (ETA), Technological tools and devices, Transparent monitored supply chains, Visibility in logistics.

RELATED TOPICS

Innovative and smart technologies in logistics and supply chains, Best practices in logistics and supply chains, Logistics 4.0, Supply Chain 4.0

INTEGRATING BLOCKCHAIN AND SUSTAINABILITY: A LITERATURE-BASED DESIGN FOR TURKISH-EGYPTIAN APPAREL COLLABORATION

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ABSTRACT:
Purpose:
This study introduces the Mediterranean Agile-Green Textile Alliance (MAGTA), an AI-enabled Turkish-Egyptian ecosystem project designed to address vulnerabilities in the global apparel supply chain.
Study design/methodology/approach:
Through a systematic literature review (SLR) encompassing 94 practitioner sources and 30 peer-reviewed studies (2020-2025), a strength-weakness-opportunity-threat (SWOT) analysis was conducted within a qualitative antecedent-design-outcome (ADO) framework.
Findings:
MAGTA incorporates three principal components: a dual-hub architecture with blockchain compliance, an eco-denim hub, and a skills academy. The project seeks to merge the rapidity of near-shoring with duty-free access, while aligning with European Union textile strategies and sustainability goals. MAGTA presents an integrated people-planet-prosperity value proposition by enhancing living wages and skills, reducing carbon emissions, and securing blended, green finance.
Originality/value:
This literature-driven design illustrates the potential for implementing supply chain innovations in data-scarce, high-risk regions, addressing critical weaknesses in the global apparel industry, such as fast-fashion volatility, conflict-related shipping delays, and inadequate social audits.

KEYWORDS:
AI, apparel, blockchain, Egypt, sustainability, Turkey

RELATED TOPICS:
Sustainability in logistics and supply chains, production management, foreign trade

FROM SILOED SYSTEMS TO FEDERATIONS OF PLATFORMS A SHARED ECOSYSTEM: DIGITAL COLLABORATION AS THE SHIPPER'S GATEWAY TO THE PHYSICAL INTERNET

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ABSTRACT:
This paper analyzes the evolution of the digitalization of international logistics from the perspective of shippers and argues that the key way to realize the efficiency, sustainability and flexibility benefits envisioned by the Physical Internet (PI) vision is through a strategic transformation that fosters digital collaboration through federation of platforms

The current state of global logistics can be illustrated by high costs for shippers, unavoidable inefficiencies, constant disruptions and operational complexities, and never being able to see the whole picture.

Bu using qualitative case study analysis to examine current digital platforms and emerging technologies, starting from the first wave of digitalization to today's AI-powered solutions. It also makes future projections of logistics digitalization from shippers' perspective.

The main findings of this article are the trends in digital systems in logistics, from silo-based platforms to cross-functional platforms, from supplier-centric platforms to carrier-centric platforms, and the creation of architectures that target mutual data exchange and collaboration rather than just traceability.

The main motivations that will enable these platforms to achieve success today and main reasons for the failure of Blockchain-based platforms such as TradeLens in the past have been identified.

It concludes by proposing a phased, actionable roadmap for logistics platforms to navigate this transition and offers recommendations designed to accelerate the evolution toward ecosystem logistics to achieve Physical Internet (PI) vision.

KEYWORDS
Ecosystem Logistics, Logistics Platforms, Physical Internet (PI),

RELATED TOPICS
Resilient logistics and supply chains, Logistics management, Best practices in logistics and supply chains

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THE ROLE OF ARTIFICIAL INTELLIGENCE ALGORITHMS IN ACHIEVING GREEN LOGISTICS OBJECTIVES

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ABSTRACT:
Purpose:
Green logistics management is all about reducing and, ideally, eliminating negative environmental impacts and consequences at every stage of logistics processes. It aims to achieve financial, social and environmental profitability simultaneously. Digital transformation can provide a valuable opportunity to support the maximisation of these profitability areas. That is why risk management experts are currently focusing on improving their digital transformation capabilities.
Organisations have recognised that integrating environmental considerations into their business practices can enhance their social, financial and reputational performance. Furthermore, by implementing green and lean practices, they can also conserve resources and eliminate unnecessary burdens on employees. Organisations with a high level of awareness, based on a risk management philosophy, decide to incorporate green logistics practices into their processes.
With these assumptions, the purpose of this study is to examine the critical role and potential contributions of Artificial Intelligence (AI) algorithms in achieving green logistics objectives. It aims to compile and analyze the innovative solutions offered by AI in reducing the environmental footprint of logistics operations, increasing resource efficiency, and creating a sustainable supply chain ecosystem.
Study design/methodology/approach:
The research is based on a conceptual review of existing literature, as well as best practices, within a conceptual framework. By reviewing academic papers, industry reports, and case studies that explore the intersection of green logistics and AI, the potential of AI algorithms in mitigating the environmental impacts of logistics processes is presented. The integration of various AI techniques such as machine learning, deep learning and optimisation algorithms into green logistics applications is analysed.
Findings:
Research findings clearly indicate that artificial intelligence algorithms, when integrated into logistics applications through digital transformation, have the potential to provide significant opportunities in achieving green logistics goals and thereby supporting corporate sustainability. The importance of green practices in capturing various environmental opportunities, extending from resource savings to carbon footprints, is increasingly recognised, and their philosophy is beginning to be understood. Green practices entail the development of an organisational culture that incorporates green management. By increasing the accuracy of demand forecasting, AI helps to prevent excess inventory and unnecessary storage costs, while making waste

management and recycling processes more efficient. Furthermore, the potential and effectiveness of AI in high-risk areas have been identified. These areas include maintaining fuel efficiency through predictive maintenance in fleet planning and management, as well as optimising energy consumption in warehouse operations.

Originality/value:

It is very important to see the potential results of new generation managerial applications in practice in order to spread these applications and also to have them owned by managers and employees, namely the society. Thus, progress can be made in green cultural transformation. This study aims to clarify and concretize the situation by integrating artificial intelligence algorithms and green logistics goals through a multifaceted and holistic perspective, and by relating theoretical possibilities to practical applications. It aims to contribute to both academic literature and the field of supply chain management (and/or logistics management) by providing a holistic view of the potential of AI to support performance in logistics in various ways for decision-makers and industry professionals. The article emphasizes that AI is not only a tool for operational efficiency and cost reduction, but also a strategically important lever in terms of environmental capacity and performance.

KEYWORDS

Artificial Intelligence, AI-based Logistics, Green Logistics, Sustainable Supply Chain, Supply Chain Management, Sustainability.

RELATED TOPICS

Sustainability in logistics and supply chains, Logistics 4.0.

EVALUATION OF DISTRIBUTION CENTER SCENARIOS IN COMMERCIAL COOLING SECTOR

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ABSTRACT:
Purpose:
This study aims to define the effects of alternative distribution center locations on the overall performance of a supply chain network in the commercial cooling industry. The research focuses on how network design decisions influence transportation costs, time and emissions, particularly in systems with limited production facilities and warehouse availability.
Study design/methodology/approach:
A mixed-integer linear programming model was developed to simulate a realistic logistics system that includes forward flows. The model integrates constraints related demand, emissions, and capacity limits in regional disposal centers and distribution centers. Three scenarios were tested by introducing different distribution center configurations across Europe, using data from an industry case.
Findings:
The analysis reveals that changes in distribution center placement can significantly impact logistical efficiency and environmental indicators. For example, adding a distribution hub in Poland reduced average transport distances and emissions by up to 15%. However, the capacity of distribution centers may limit the benefits in some regions.
Originality/value:
This study offers a practical perspective on distribution network planning by combining cost-efficiency with environmental considerations in a fixed supply chain structure. It highlights how companies can make location decisions that align with both operational and strategic goals. It provides a structured framework for manufacturers/suppliers aiming to integrate sustainability in logistic decisions.
KEYWORDS
Emissions optimization, Location analysis, Supply Chain Planning
RELATED TOPICS
Location selection, Sustainability in logistics and supply chains

POST-EARTHQUAKE VACCINE DISTRIBUTION: A REVIEW AND FUTURE RESEARCH DIRECTIONS

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ABSTRACT:
Purpose:
This study aims to analyze existing approaches, focusing on post-earthquake vaccine logistics, which has not been adequately addressed in the growing body of vaccine distribution models in the literature, particularly after the COVID-19 pandemic. A holistic vaccine distribution model is needed to address the secondary health crises caused by epidemics that emerge after earthquakes that cause physical destruction. This study aims to contribute to the literature by addressing this unique gap in the literature.
Study design/methodology/approach:
This study conducted a thematic categorization and analysis of studies using Scopus and Web of Science databases. Five themes were explored within the scope of the review: (i) basic optimization models in vaccine logistics, (ii) epidemic-based vaccine logistics models, (iii) hybrid transportation systems in vaccine logistics, (iv) vaccine distribution models using artificial intelligence and metaheuristic methods, and (v) models specific to post-earthquake vaccine distribution.
Findings:
Results demonstrate that while Artificial Intelligence-based models have gained prominence in recent years, most studies focus solely on epidemic dynamics and are not suitable for multi-disaster scenarios. In particular, vital logistics factors such as cold chain disruptions and infrastructure damage have not been adequately addressed in most models. Models that incorporate epidemiological models that allow for disease spread prediction into disaster logistics scenarios are quite limited.
Originality/value:
This paper presents a review focusing on the gap, demonstrating the need for models that provide adaptable logistics solutions for multi-disaster scenarios, in contrast to the single-disaster-focused approaches that dominate the vaccine logistics literature.

KEYWORDS
Disaster Logistics, Optimization Models, Review, Vaccine Logistics

RELATED TOPICS
Health care logistics and supply chains, Humanitarian logistics and supply chains, Emergencies and crisis logistics and supply chains, Artificial Intelligence in logistics and supply chains

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ARTIFICIAL INTELLIGENCE-DRIVEN APPROACHES FOR MARITIME ROUTE OPTIMIZATION: A COMPREHENSIVE REVIEW OF METHODS, DATA, AND CHALLENGES

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ABSTRACT:

Route optimization in maritime transportation is a complex problem requiring the balance of multiple objectives such as operational efficiency, navigational safety, environmental sustainability, and compliance with international regulations. Achieving this balance demands the simultaneous consideration of various operational and environmental factors. Traditional algorithmic methods primarily rely on static rules and predefined waypoints, which limit their ability to adapt to the dynamic and unpredictable nature of maritime environments.

In recent years, Artificial Intelligence (AI)-based systems have introduced significant innovations in this field. By integrating meteorological data, vessel performance metrics, and operational constraints, these systems enable the development of dynamic and flexible route planning solutions. Machine learning techniques identify optimal speed-route combinations by analyzing historical voyage data, while computer vision and sensor fusion methods are effectively applied in collision avoidance systems. Additionally, forecasting systems based on long-term climate and weather data support the formulation of seasonal routing strategies.

This study aims to provide a comprehensive review of current AI-supported route optimization approaches and technological developments. The methods discussed in the literature will be evaluated in terms of data sources, algorithmic approaches, performance metrics, and application scenarios. The goal is to offer a critical analysis of prevailing trends and the technical and operational challenges faced.

KEYWORDS

Maritime transportation, Route optimization, Artificial Intelligence (AI), Machine learning (ML).

RELATED TOPICS

Artificial Intelligence in logistics and supply chains, Autonomous vehicles in logistics and supply chains

MODELING RADIOACTIVE DRUG DISTRIBUTION as VEHICLE ROUTING PROBLEM WITH TIME-WINDOW CONSTRAINTS

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ABSTRACT:

Purpose:

Radioactive drugs (also called radiopharmaceuticals) are distributed within a specialized logistics network in the healthcare sector due to their short half-life and special handling requirements. This study specifically considers Fluorodeoxyglucose (FDG), a radioactive drug widely used in diagnostic health applications such as Positron Emission Tomography (PET) scans. Due to its short half-life of only 110 minutes, FDG must be transported to demanding PET locations without losing its required effectiveness. Therefore, the transport of FDG must be optimized to ensure that it arrives at healthcare facilities in a safe, efficient, and cost-effective manner, all while complying with strict time constraints. We aim to model the delivery operations of a radiopharmaceuticals company based in Istanbul and serving to Marmara region in order to assist its planning process.

Study design/methodology/approach:

We first translate the amount of doses demanded from PET locations to the required time-window estimates. Then, we formulate a vehicle routing problem with time windows for FDG distribution (VRPTW-FDG), which minimizes the total travel distance while satisfying the vehicle capacity and time windows. We also introduce an exact solution to VRPTW-FDG for a small set of PET locations and a heuristic solution for larger customer network using genetic algorithm.

Findings:

Our results illustrate that the use of VRPTW-FDG might yield further cost reduction in FDG transportation. It can also be used as a decision support system to enhance the efficiency of radiopharmaceuticals production and delivery planning process.

Originality/value:

Studies on the delivery of radiopharmaceuticals focus on handling, dose methods, and often overlook transport costs due to high production costs. This study attempts to fill this gap merely looking at transportation costs from routing perspective by translating decay of FDG into time constraints.

KEYWORDS

Vehicle Routing Problem with Time Window, Radioactive Drug Distribution, Optimization, Transportation, Genetic Algorithms

RELATED TOPICS

Transportation and logistics law, Logistics management

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PRIORITIZING GENERATIVE AI APPLICATIONS IN SUPPLY CHAINS: A PROCESS-BASED EVALUATION MODEL

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ABSTRACT:
Purpose:
This study aims to explore how generative artificial intelligence technologies can be strategically integrated into various supply chain processes to enhance sustainability, operational efficiency, and resilience. By identifying which functions benefit most from generative intelligence, the study supports decision-makers in targeting their AI investments effectively.
Study design/methodology/approach:
A process-based evaluation model was developed to assess the impact of generative artificial intelligence across core supply chain activities, including demand forecasting, transport planning, inventory control, product design, and reverse logistics. A mixed-methods approach was adopted, combining literature analysis with expert assessments to prioritize these applications based on their effectiveness and feasibility in real-world operations.
Findings:
The results indicate that demand forecasting and risk management are the most responsive areas for generative artificial intelligence integration due to their data-driven and scenario-based nature. In contrast, processes involving ethical judgment or complex stakeholder dynamics, such as supplier negotiations, require human oversight and are less suited to fully autonomous AI solutions. The research highlights the potential of generative artificial intelligence to drive digital transformation while supporting sustainability and agility in supply chains.
Originality/value:
This paper offers a structured framework to guide organizations in the prioritization of generative artificial intelligence tools within supply chains. Unlike existing studies that focus on general AI, this work emphasizes the unique role of generative intelligence in creating predictive and adaptive solutions tailored to dynamic logistics environments. The framework contributes to the strategic alignment of technology adoption with sustainable and resilient supply chain practices.

KEYWORDS
Supply Chain Management; Digitalization; Generative Artificial Intelligence; Multi-Criteria Decision Making Models
RELATED TOPICS
Generative Artificial Intelligence, Artificial Intelligence in logistics and supply chains

LMSCM2025

DELIVERY DELAY PREDICTION IN AMAZON DATA AND EARLY WARNING ANALYSIS WITH THE PROACTIVE ADAPTATION RATE (PAR)

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ABSTRACT:
Purpose:
Customer experience management increasingly emphasizes last-mile logistics, where delivery performance directly shapes satisfaction, loyalty, and brand perception. While many studies predict delivery delays, the literature lacks metrics that explicitly evaluate the timing dimension of predictive models. This study addresses this gap by applying the Proactive Adaptation Rate (PAR) metric to delivery operations.
Study design/methodology/approach:
A dataset of 43,739 Amazon delivery records was analyzed. Early warning signals were operationalized through traffic congestion, adverse weather, and pickup delays. Deliveries were classified as on-time or delayed. Logistic Regression, Random Forest, Gradient Boosting, AdaBoost, and XGBoost were applied. Model performance was assessed with both conventional metrics (Accuracy, ROC AUC) and the PAR metric, which measures the proactivity of detection relative to the actual delivery outcome.
Findings:
Delivery delays can be predicted on average 147 minutes before customers experience them. The mean PAR score (≈ –1) confirms that early signals consistently precede the outcome. Random Forest achieved the best predictive accuracy (79.6%, ROC AUC 0.89), followed by Gradient Boosting and XGBoost. Logistic Regression showed weaker performance (68%, ROC AUC 0.75). While predictive accuracy varied across algorithms, PAR values remained stable, demonstrating that the main distinction lies in the volume of correctly identified cases rather than timing performance.
Originality/value:
This study introduces the temporal evaluation of predictive performance to logistics and marketing research, offering novel insights into how delivery delays can be mitigated proactively. By integrating operational logistics data with PAR, it bridges analytics, logistics, and customer experience management, delivering both theoretical novelty and practical managerial implications.

KEYWORDS
Customer Experience Management; Logistics; Delivery Delays; Machine Learning; Predictive Analytics; Proactive Adaptation Rate (PAR); Early Warning Signals

RELATED TOPICS
Customer Experience Management, Predictive Analytics in Logistics

THE ROLE OF GREEN HYDROGEN IN URBAN ENERGY TRANSITION: A CONCEPTUAL APPROACH TO SUSTAINABLE TRANSPORTATION STRATEGIES WITH A FOCUS ON GAZIANTEP

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ABSTRACT:

In alignment with Türkiye's national target of achieving net-zero greenhouse gas emissions by 2053, green hydrogen has emerged as a strategic component of the country's energy transition policies. Hydrogen produced from renewable sources is anticipated to gradually replace fossil fuels across multiple sectors, with urban transportation identified as a key application area. This review-based study focuses on the province of Gaziantep, a region characterized by high solar irradiance, a dense industrial landscape, and rising energy demand. It examines the existing academic literature on integrating green hydrogen into urban mobility systems and identifies associated research opportunities.

Hydrogen fuel cell electric vehicles (HFCEVs) are recognized for their advantages over battery electric vehicles, including shorter refueling times and extended driving ranges. Within this context, the study emphasizes the importance of utilizing advanced tools, including Geographic Information Systems (GIS)-based spatial analysis, multi-criteria decision-making techniques, and Mixed-Integer Programming (MIP) models, to support the strategic planning of urban-scale hydrogen infrastructure. Given Gaziantep Metropolitan Municipality's commitment to reducing CO_2 emissions by 80% by 2050, the deployment of such technologies becomes increasingly relevant.

By offering a conceptual framework, this study provides a comprehensive evaluation of scientific approaches to hydrogen-based urban transportation, aiming to contribute methodologically and strategically to future research on sustainable urban mobility.

KEYWORDS

Green Hydrogen Production, Hydrogen Supply Chain, Net-Zero Emissions, Solar Energy, Carbon Emission Reduction

RELATED TOPICS

Sustainable city logistics and supply chains,
Energy Management,
Smart and durable city logistics and supply chains,
Sustainability in logistics and supply chains

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RARE EVENTS AND COMPLEX DEPENDENCIES: APPLYING HIGH ENERGY PHYSICS SIMULATION TECHNIQUES TO LOGISTICS

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ABSTRACT:
Purpose:
This study aims to enhance logistics scenario analysis by adapting advanced Monte Carlo techniques from high energy physics (HEP). The objective is to provide a more robust framework for managing uncertainty, particularly in contexts where rare events and complex dependencies play a critical role.
Study design/methodology/approach:
The paper introduces the application of importance sampling, Markov Chain Monte Carlo (MCMC), and variance reduction methods to logistics decision-making. These techniques are adapted to address disruptions in supply chains, transportation delays, demand fluctuations, and cost volatility. The approach emphasizes the capacity of HEP-inspired methods to capture low-probability events and efficiently model high-dimensional, correlated risk factors.
Findings:
The study demonstrates that advanced Monte Carlo methods significantly improve the accuracy and efficiency of logistics simulations compared to conventional random replication approaches. Importance sampling provides deeper insights into rare but high-impact risks, MCMC enhances modeling of correlated uncertainties, and variance reduction delivers reliable results with fewer simulations.
Originality/value:
By introducing methodologies from high energy physics into logistics research, the paper contributes a cross-disciplinary framework that extends beyond the traditional use of basic Monte Carlo models. This integration strengthens risk sensitivity, supports more resilient decision-making, and highlights the value of scientific simulation techniques for complex logistics challenges.
Keywords:
high energy physics, logistics, Markov Chain Monte Carlo, Monte Carlo simulation, uncertainty management, variance reduction
Related Topics:
Logistics and Supply Chain Risk Management, Quantitative Methods in Logistics

INTEGRATION AND PERFORMANCE EVALUATION OF SMART WAREHOUSE TECHNOLOGIES USING THE COCOSO METHOD

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ABSTRACT:

Purpose: The main objective of this study is to develop an analytical decision-support framework to ensure the effective integration and performance evaluation of smart warehouse technologies within the context of Industry 4.0 transformation. The study systematically addresses multi-dimensional decision-making challenges such as technology selection, implementation strategies, and performance assessment concerning the integration of advanced digital technologies including robotic systems, Internet of Things and machine learning into warehouse operations. The study offers a holistic evaluation approach to identify optimal technology combinations by considering critical criteria such as operational efficiency, cost effectiveness, flexibility, technical compatibility, and sustainability.

Study design/methodology/approach: In this context, the CoCoSo Method one of the prominent multi criteria decision making techniques is applied to evaluate alternative technologies based on multi dimensional criteria. The method presents a hybrid analytical framework that merges the weighted sum and weighted product models to assess the relative performance of technologies, using criterion weights derived from expert opinions and sectoral data. The assessment process consists of determining criteria, assigning weights, scoring alternatives, and applying the CoCoSo algorithm.

Findings: The analysis reveals that the integration of technologies requires not only operational efficiency but also strategic planning in terms of flexibility and sustainability. The structured insights provided by the CoCoSo Method offer a transparent, consistent, and data-driven evaluation framework for decision-makers in selecting appropriate technologies.

Originality/value: This study develops a novel analytical approach that can be utilized in evaluating smart warehouse systems, a key component of digital transformation in the logistics sector. It contributes to the practical application of Industry 4.0 principles and provides strategic guidance for policymakers and stakeholders in areas such as technology selection, integration strategy development, and enhancement of operational resilience.

KEYWORDSS

CoCoSo Method, Industry 4.0, Smart Technologies, Smart Warehouse Management.

RELATED TOPICS

Supply Chain Management, Logistics Management, Industry 4.0.

LMSCM2025

COMPARATIVE ANALYSIS OF E-COMMUNICATION STRATEGIES OF MALL LOGISTICS COMPANIES

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ABSTRACT:
Purpose:
The purpose of this study is to examine and compare the websites of logistics companies serving shopping malls (malls) to identify how they communicate their services, operational capabilities, and value propositions to potential customers and stakeholders.
Study design/methodology/approach:
A qualitative content analysis was conducted on a sample of mall logistics companies operating in Türkiye. The analysis focused on several dimensions, including service scope and description, operational transparency, availability of digital communication tools (such as contact forms, live chat, and social media links), emphasis on sustainability initiatives, and website user experience. The evaluation criteria were systematically coded to enable cross-company comparison and highlight differences in digital presence.
Findings:
The analysis is still in progress; comprehensive findings will be included in the full manuscript submission.
Originality/value:
This study contributes to the literature by emphasizing the strategic role of corporate websites in the mall logistics sector and offers a framework for evaluating digital communication effectiveness. The findings provide both academics and practitioners with insights into competitive positioning and opportunities for improving customer-oriented digital strategies.

KEYWORDS
Content analysis, Digital communication, Digital marketing, Mall logistics, Website comparison.

RELATED TOPICS
Innovative and smart technologies in logistics and supply chains, Sustainable city logistics and supply chains, Smart and durable city logistics and supply chains

FRAMING EFFECT FILTER USABILITY USING GENERATIVE AI THROUGH SUSTAINABLE SUPPLIER SELECTION

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ABSTRACT:
Purpose:
Framing effect is one of the cognitive biases in decision making. It is aimed to determine whether framing effect filter as a debiasing strategy is usable or not using a generative artificial intelligence tool through sustainable supplier selection.
Study design/methodology/approach:
Experiments carried out based on prompts to determine the usability of framing effect filter. Prompts were generated based on traditional pairwise comparisons and framing effect filter comparisons.
Findings:
The finding shows that the framing effect filter is usable. Deeper insights gained using post-prompts.
Originality/value:
To the best of the author's knowledge, this is the first effort to use generative artificial intelligence in cognitive biases in multi criteria decision making.

KEYWORDS
cognitive bias, debiasing, framing effect, generative artificial intelligence, multi criteria decision making, sustainable supplier selection

RELATED TOPICS
Generative Artificial Intelligence, Sustainability in logistics and supply chains, Artificial Intelligence in logistics and supply chains

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SISTER DISASTER PARK APPROACH FOR DISASTER-RESILIENT CITIES: PILOT PROVINCE SELECTION ON THE YEDISU FAULT LINE

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ABSTRACT:
Purpose:
Disaster-resilient cities are defined as urban areas that are prepared for natural disasters, flexible, and able to recover quickly. This study aims to propose the "Sister Disaster Parks" model as a new approach to enhance resilience in cities located along the Yedisu fault segment.
Study design/methodology/approach:
Criteria derived from the literature were weighted using the Analytic Network Process (ANP). The alternatives (provinces around the Yedisu fault) were then ranked using the TOPSIS method to identify the most suitable location for initiating the Sister Disaster Parks model.
Findings:
The analysis indicated that Erzincan emerged as the most suitable city due to its relative advantages in resilience-related factors. This finding highlights the importance of integrating physical and social infrastructure considerations with hierarchical coordination mechanisms in disaster park planning.
Originality/value:
The study introduces the Sister Disaster Parks concept, inspired by the sister cities model, but extended to include both horizontal cooperation and hierarchical coordination among parks. This original approach offers a new framework for disaster-resilient urban planning, particularly for regions with high seismic risk such as the Yedisu fault line.
KEYWORDS
Disaster Management, Disaster Park, Sister Disaster Park
RELATED TOPICS
Resilient logistics and supply chains, Service supply chains

LMSCM2025

A COMPREHENSIVE LITERATURE REVIEW ON THE APPLICATION OF SIMULATED ANNEALING IN SUPPLY CHAIN OPTIMIZATION

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ABSTRACT:
Purpose:
This study aims to provide a comprehensive examination of the application of simulated annealing (SA) algorithms in solving complex supply chain optimization (SCO) problems. The goal is to assess how SA has been utilized across various supply chain functions and to identify its effectiveness, limitations, and potential for future research.
Study design/methodology/approach:
A systematic literature review was conducted by analyzing peer-reviewed articles published between 2005 and 2025, sourced from databases such as Web of Science, Scopus, IEEE Xplore and ScienceDirect. The reviewed works were categorized according to the supply chain problem addressed (e.g., vehicle routing, facility location, inventory management, and production planning) and the role of SA in hybrid or metaheuristic frameworks. Special attention was given to algorithmic design choices, such as neighborhood structures, cooling schedules, and integration with other optimization techniques.
Findings:
Simulated annealing has demonstrated strong performance in tackling NP-hard problems in supply chain contexts, especially for discrete combinatorial tasks like vehicle routing and facility layout. It is often preferred for its simplicity, flexibility, and ability to escape local optima. Recent studies increasingly integrate SA with other heuristics or meta-heuristics (e.g., genetic algorithms, tabu search) to enhance solution quality and convergence speed. However, issues such as parameter tuning sensitivity and computational time remain challenges for large-scale, real-time applications.
Originality/value:
This review synthesizes 20 years of research on SA in supply chain optimization, offering a structured overview and highlighting best practices and research gaps. It provides actionable insights for both academics and practitioners seeking efficient heuristic and meta-heuristic approaches to complex supply chain problems.

KEYWORDS
Combinatorial Optimization, Literature Review, Metaheuristics, Simulated Annealing, Supply Chain Optimization.
RELATED TOPICS
Supply Chain 4.0, Innovation and R&D in logistics and supply chains.

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EARLY DETECTION OF SUPPLY CHAIN DIRUPTIONS USING GOOGLE TRENDS AND ECONOMIC INDICATORS

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ABSTRACT:
Purpose: This study investigates whether digital behavioral data, specifically Google search interest in key supply chain terms, can serve as early indicators of global supply chain stress. The research aims to explore the relationship between public search behavior and traditional economic indicators to develop enhanced monitoring frameworks for supply chain disruptions.
Study design/methodology/approach: The analysis employs Pearson correlation analysis on 261 weekly observations spanning June 2020 to June 2025. Google Trends data for five supply chain-related keywords (supply shortage, supply chain crisis, shipping delay, container shortage, port congestion) were collected and matched with Baltic Dry Index values. Data preprocessing included weekly alignment, missing value treatment, and z-score anomaly detection. Statistical significance was evaluated using t-tests with $p < 0.05$ threshold.
Findings: The keyword "port congestion" demonstrated the strongest correlation with Baltic Dry Index ($r = 0.678$, $p < 0.001$), followed by "container shortage" ($r = 0.605$, $p < 0.001$). These two terms explain 46.0% and 36.6% of BDI variance respectively. Peak search activity frequently aligned with or preceded major supply chain disruptions, particularly during the 2021 crisis period. The analysis revealed distinct phases: crisis peak (2021), recovery (2022), and stabilization (2023-2025). Year 2021 showed the highest correlation strength, with port congestion searches increasing 6.2 times compared to pre-crisis levels.
Originality/value: This research contributes to supply chain monitoring literature by demonstrating that open behavioral data can complement conventional economic indicators. The study provides empirical evidence for integrating Google Trends into early warning systems, offering supply chain managers and policymakers a cost-effective tool for proactive disruption management. The findings suggest that public search behavior reflects real-time supply chain stress more immediately than traditional lagging indicators

KEYWORDS
Baltic Dry Index, digital behavior analysis, early warning systems, Google Trends, supply chain disruptions, supply chain monitoring.

RELATED TOPICS
Supply Chain Risk Management, Digital Supply Chain Analytics

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THE ECONOMIC CONTRIBUTION OF ARTIFICIAL INTELLIGENCE IN THE TURKISH HEALTHCARE SECTOR: 2030 PROJECTION

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ABSTRACT:
Purpose: This study aims to estimate the economic impact of artificial intelligence (AI) on the Turkish healthcare sector by 2030. It evaluates AI's contributions to diagnostics, treatment, hospital management, and chronic disease monitoring, which are critical for healthcare policies and technological investment strategies. Although AI is already optimizing health services in Turkey, local economic projections remain scarce. This study, supported by real data (TÜİK, Ministry of Health), employs quantitative methods to project an economic contribution of approximately 6.5 billion TL (812.5 million USD) by 2030. Realizing this potential depends on investment incentives and robust data infrastructure.
Study design/methodology/approach: The research is based on data from 2018 to 2024 and projects outcomes for the period of 2024 to 2030. It utilizes reports from TÜİK Health Statistics Yearbooks, Turkish Ministry of Health's Digital Health Strategy Reports, OECD Health Statistics, and McKinsey Global Institute's AI in Healthcare Reports.
Findings: The analysis predicts that by 2030, AI could contribute 2 billion TL in diagnostics, 3 billion TL in hospital management, and 1.5 billion TL in chronic disease monitoring, totaling an estimated economic impact of 6.5 billion TL (812.5 million USD). The study recommends investment incentives, strengthened data infrastructure, and ethical frameworks to harness this potential.
Originality/value: This research presents a unique economic projection focused on AI's role in Turkey's healthcare system. It delivers reliable, applicable insights supported by empirical data and provides a strategic basis for policy-making and technological investments.
KEYWORDS
Artificial intelligence, economic development, digital transformation, healthcare management
RELATED TOPICS
Artificial Intelligence, Digital Transformation, Healthcare Management

THE MEDIATING ROLE OF DIGITAL LITERACY IN THE EFFECT OF TALENT MANAGEMENT IMPLEMENTED IN PRIVATE SCHOOLS ON TEACHERS' INDIVIDUAL ENTREPRENEURSHIP AND INNOVATIVE BEHAVIOUR CAPACITIES

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ABSTRACT:

The primary aim of this study is to reveal the mediating role of digital literacy in the effect of talent-management practices implemented in private schools on teachers' individual-entrepreneurship and innovative-behaviour capacities. Planned as a relational field study, the research employs the descriptive-correlational survey design, a quantitative research method. The study group comprises 627 high-school educators (teachers and administrators) selected by simple random sampling from private high schools located in the districts of Istanbul under the Ministry of National Education during the 2024-2025 academic year. Data were collected by questionnaire. In this context, four different scales were used to determine teachers' levels of Talent Management, Individual Entrepreneurship, Innovative Behaviour Capacity and Digital Literacy. According to the analyses, the proper implementation of Talent Management plays a significant role in increasing teachers' levels of Individual Entrepreneurship and Innovative Behaviour Capacity, while Digital Literacy, although not directly influential, has a positive indirect effect on the relationships among these variables. Likewise, it was concluded that raising teachers' Digital-Literacy levels is important for enhancing their entrepreneurial and innovative capacities.

KEYWORDS

Digital Literacy, Individual Entrepreneurship, Innovative Behaviour Capacity, Talent Management.

RELATED TOPICS

Business Administration, Management.

LMSCM2025

GENERATIVE AI–ASSISTED COMPLIANCE AND OPERATIONS OPTIMIZATION FOR MARITIME TRANSPORT UNDER EU ETS AND IMO REGULATIONS

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ABSTRACT:
Purpose:
This study aims to address the increasing compliance complexity in maritime transport arising from the extension of the EU Emissions Trading System (EU ETS), the FuelEU Maritime regulation, and the International Maritime Organization's (IMO) CII and EEXI requirements. The objective is to design a decision support framework that enables shipping companies to balance regulatory compliance with operational efficiency and service reliability.
Study design/methodology/approach:
The proposed system integrates Automatic Identification System (AIS) data, digital twin simulation, and mixed-integer linear programming (MILP) optimization. It consists of three main elements: (i) a digital twin simulating vessel operations under varying routes, speeds, and fuel mixes; (ii) a MILP optimization model minimizing total costs—including fuel expenditures, EU ETS allowance purchases, and FuelEU penalties—while ensuring service-level compliance; and (iii) a large language model (LLM) agent that dynamically parses evolving EU and IMO regulatory texts and updates the optimization parameters accordingly.
Findings:
By evaluating short-, medium-, and long-haul routes under different congestion and fuel availability conditions, the study identifies critical trade-offs between emission compliance and service reliability. Results highlight the conditions under which investments in alternative fuels, slow steaming, or proactive allowance trading yield more favorable compliance–cost outcomes.
Originality/value:
The paper contributes by introducing a Generative AI–enabled compliance–operations framework for maritime transport, combining digital twin simulation with optimization and real-time regulatory intelligence. This novel LLM-to-optimization pipeline provides actionable insights for shipping companies, with a particular focus on Eastern Mediterranean routes, where compliance pressures and operational uncertainties are highly pronounced.

Keywords:
AIS data, compliance management, digital twin, emissions trading, generative AI, maritime transport, optimization

Related Topics:
Maritime Logistics, Digitalization and Sustainability in Logistics

EVALUATION OF SUSTAINABILITY PERFORMANCE IN ROAD TRANSPORTATION USING FUZZY AHP: THE 2026 FRAMEWORK

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ABSTRACT:
Purpose:
This study aims to analyze the critical elements established to achieve sustainability goals within the ESG (Environmental, Social, and Governance) framework in the road freight transportation sector. Based on expert evaluations, the research seeks to determine the relative importance and ranking of these criteria, prioritizing both main and sub-criteria to establish a strategic hierarchy from most to least significant.
Study design/methodology/approach:
The study adopts a multi-criteria decision-making approach using the Fuzzy Analytic Hierarchy Process (AHP). Data were collected through structured evaluations from seven experts in managerial positions within the road transportation sector. The methodology involves the assessment of 4 main criteria and 17 sub-criteria, utilizing linguistic scales to capture expert judgments. These qualitative assessments are converted into triangular fuzzy numbers to ensure a realistic mathematical ranking while minimizing subjectivity. Furthermore, the process includes a consistency analysis to validate the reliability of the expert-weighted data within a fuzzy environment.
Findings:
The results reveal that the economic criterion is the primary priority for decision-makers, followed by environmental, social, and governance dimensions, respectively. Within the sub-criteria, operation cost along with efficiency and speed emerge as the most critical factors for economic sustainability. In the environmental dimension, management certificates and waste management are prioritized, while labor rights and driver safety stand out as key social priorities. For governance, legal regulations and transparency are identified as the most vital elements.
Originality/value:
This study contributes to the literature by providing a structured ESG-based evaluation framework specifically tailored for the road freight transportation sector. Its originality lies in using Fuzzy AHP to reveal how decision-makers prioritize economic viability alongside environmental and social responsibilities, effectively bridging the gap between theoretical sustainability and sectoral practice. The research offers a strategic roadmap for policymakers and logistics companies to develop regulatory-compliant strategies and provides a foundational basis for future studies across different transport modes and geographical regions.

KEYWORDS
ESG, Fuzzy AHP, Green Logistics, Road Freight Transportation, Sustainability Assessment

RELATED TOPICS
Sustainability in logistics and supply chains, Green logistics and supply chain management, Big data analytics in logistics and supply chains

TRADE WARS AND TURKISH LOGISTICS: A QUALITATIVE ANALYSIS OF TRUMP-ERA TARIFF IMPACTS

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ABSTRACT:
Purpose:
International trade is undergoing significant changes due to complex rules and policies designed by major economic powers, including the USA and China, as well as multilateral organizations such as the World Trade Organization (WTO). The trend of protectionism has risen dramatically, particularly with President Trump's 2025 tariff. It has been described as protectionist measures the USA is taking in response to China's exports, thus creating a trade war between the two nations. This trade war affected not only two countries but the entire world as well. Therefore, the aim of this study is to examine how Trump's tariff policies impact the Türkiye's supply chains.
Study design/methodology/approach:
This research employs a qualitative method approach, drawing on the technique to comprehensively understand how trade wars affect Türkiye's supply chain management. In this study, semi-structured interviews with four experts who works as managers in supply chain department and two academics. Structured literature reviews are also conducted to make data triangulation possible. Integrating the findings with relevant academic literature on trade wars' effects on Türkiye's supply chain enhances the validity and reliability of the study.
Findings:
This study reveals three primary outcomes for Türkiye's supply chain. Firstly, foreign policy and trade shifts have exposed Turkish supply chains to vulnerability. Secondly, firms can diversify markets and suppliers by increasing exports and imports to the European Union, Russia, and China, resulting in a new trade policy that is strategically adapted. Lastly, tariffs are both constraints and opportunities for Turkish supply chains. It is possible for some Turkish sectors to penetrate European markets or to replace Chinese exports with their own.
Originality/value:
The study provides a unique perspective on how Turkish supply chains interpret and navigate this trade war. This paper combines expert opinion and literature to enhance our understanding of Turkish supply chains' strategic resilience and agility in the face of global policy volatility.

KEYWORDS
Logistics sector, Supply chain resilience, Tariff policies, Trade wars, Türkiye.

RELATED TOPICS
Resilient logistics and supply chains, Logistics management, Risk management

HISTORICAL DEVELOPMENT AND COMPARATIVE ANALYSIS OF DIGITAL MATURITY ASSESSMENT METHODOLOGIES

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ABSTRACT:

Purpose:

Today, many companies are striving to increase their digital maturity levels in order to remain competitive. Due to the rapid transition to the project development stage, most of these projects either fail or are abandoned halfway through. Therefore, it is necessary to assess digital maturity before moving to the project phase. The main purpose of this study is to research digital maturity methodologies and conduct a comprehensive analysis. Companies can benefit from this study to gain comprehensive information about digital maturity assessments.

Study design/methodology/approach:

In this study, a detailed literature review and scale analysis were conducted in this field. Based on the results of the literature review, the most suitable analysis for companies was determined, and a research design was presented on how to operate this structure by selecting a scale in line with this.

Findings:

There are numerous digital maturity assessment methodologies from various countries on the market. Many of them have been developed with a focus on different sectors. However, when considering both their academic background and applicability, there are only a few digital maturity assessment methodologies that can be offered to companies. This study identified the most appropriate digital maturity assessment methodologies that enable companies to maximize their digital maturity levels.

Originality/value:

This study guides companies in selecting a digital maturity assessment methodology. Digital maturity assessments have been analyzed and compared alongside their historical development, providing readers with comprehensive research. In addition, comparative analysis will enable researchers to better distinguish between the strengths and weaknesses of methodologies.

KEYWORDS

Digital Maturity, Digital Maturity Assessment, Digital Transformation, Technology Adoption

RELATED TOPICS

Innovation and technology management, Supply Chain 4.0, Logistics 4.0

LMSCM2025

PSYCHOLOGICAL RESOURCES AND INNOVATIVE WORK BEHAVIORS OF EMPLOYEES IN DIGITAL SUPPLY CHAINS

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ABSTRACT:
Purpose:
In the age of digitalization and artificial intelligence, the sustainability and resilience of supply chains depends not only on technological infrastructures but also on human resources capable of effectively using these systems. In this context, employees' psychological well-being and their perceptions of self-efficacy regarding their creative abilities are crucial as key determinants of innovative work behaviors. The aim of this study is to examine the impact of the psychological well-being of information technology (IT) sector employees on innovative work behaviors and the mediating role of creative self-efficacy in this relationship. In light of the findings, we discuss the importance of the human factor in the transformation of digital supply chains.
Study design/methodology/approach:
The study was conducted with 302 employees working in the IT sector in Türkiye. Data were collected via an online survey using the Psychological Well-Being Scale, the Creative Self-Efficacy Scale, and the Innovative Work Behavior Scale, and analyzed using PLS-SEM.
Findings:
Findings indicate that psychological well-being has a direct effect on both creative self-efficacy ($\beta=0.511$, $p<0.001$) and innovative work behaviors ($\beta=0.235$, $p<0.001$). Furthermore, creative self-efficacy strongly predicts innovative work behaviors ($\beta=0.508$, $p<0.001$) and acts as a mediator in the effect of psychological well-being on innovative work behaviors ($\beta=0.259$, $p<0.001$).
Originality/value:
The results highlight the critical role of the human factor in digital transformation processes. Employees with high psychological well-being and a strong sense of creative self-efficacy appear to make more innovative contributions to business processes. When considered within the context of supply chain management, these findings suggest that to effectively utilize the opportunities offered by artificial intelligence and digital technologies, organizations must focus not only on technology but also on strengthening employees' psychological resources.

KEYWORDS
Creative self-efficacy, digital supply chains, human factors, innovative work behaviors, psychological well-being

RELATED TOPICS
Innovation and R&D in logistics and supply chains, innovation and technology management

CLUSTERING-BASED CLASSIFICATION OF COUNTRIES ACCORDING TO LOGISTICS PERFORMANCE

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ABSTRACT:
Purpose:
The aim of this research is to classify countries according to their logistics performance using World Bank indicators. By applying clustering analysis to the Logistics Performance Index and related variables, countries will be grouped as high-performing, moderately developed, and logistically vulnerable. This classification is intended to contribute to the analytical comparison of logistics development levels and to the conceptual debates in the academic literature.
Study design/methodology/approach:
Clustering analysis is employed to classify countries based on logistics-related indicators obtained from the World Bank. Key variables include the Logistics Performance Index and its sub-dimensions, as well as complementary trade and transport statistics. Prior to clustering, data are standardized to account for scale differences across variables.
Findings:
The clustering results reveal three distinct groups of countries with regard to logistics performance: high-performing logistics systems, moderately developed logistics infrastructure, and logistically vulnerable structures. The findings highlight significant disparities across regions, reflecting both structural strengths and weaknesses in global logistics.
Originality/value:
A contribution to the logistics literature is made by offering a clustering-based classification of countries using World Bank indicators. Unlike descriptive rankings, the analysis provides an analytical framework that identifies structural similarities and differences across nations, thereby enriching academic debates on logistics performance and development.

KEYWORDS
Clustering Analysis, Logistics Performance Index, World Bank Indicators, Data Analysis

RELATED TOPICS
Big data analytics in logistics and supply chains, Logistics management, Logistics corridors and centers, Sustainability in logistics and supply chains.

LMSCM2025

COMPRESSION OF SENSOR DATA IN LOGISTICS USING WAVELET TRANSFORM FOR AI MODEL INTEGRATION

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ABSTRACT:

Purpose:

Sensors used in logistics systems, such as those measuring location, temperature, humidity, vibration, and shock, continuously generate high-frequency data. This creates a significant burden on data storage and transmission processes. The aim of this study is to compress sensor data using a wavelet transform-based approach to reduce data size without significant information loss. In addition to improving storage and transmission efficiency, the study also considers the potential use of compressed data as input for artificial intelligence models in logistics applications.

Study design/methodology/approach:

In this study, a wavelet transform-based approach is proposed for compressing sensor data used in logistics. The method is applied to time-series data with the aim of reducing data size while preserving essential information. The approach is also evaluated in terms of its suitability for preprocessing data intended to be used as input for artificial intelligence models. The study presents the general methodology and discusses potential areas of application.

Findings:

Preliminary results of the study indicate that the wavelet transform-based compression method has the potential to significantly reduce the size of sensor data while preserving essential patterns and structures. The compressed data shows promise not only for reducing transmission and storage costs but also for serving as a suitable input for artificial intelligence models. These findings suggest practical benefits of the method in both logistics operations and AI-driven analytical systems.

Originality/value:

This study offers an original contribution by proposing a wavelet transform-based approach for compressing sensor data in the field of logistics. Unlike conventional compression methods, the proposed technique enables multi-resolution analysis and preserves essential data characteristics, making it suitable for use in data-driven systems. The study highlights the potential of compressed sensor data to serve as effective input for artificial intelligence models, thereby contributing both to efficient data management and AI-ready logistics infrastructures. Additionally, the approach may provide value for Internet of Things (IoT) applications, which are a key component of Industry 4.0 environments where real-time, large-scale sensor data processing is essential.

KEYWORDS

Data compression, Logistics, Sensor data, Supply chain, Wavelet transform, Artificial intelligence

RELATED TOPICS

Data collection technologies, Innovative and smart technologies in logistics and supply chains

A GREY-BASED MULTI-CRITERIA FRAMEWORK FOR SUSTAINABLE SUPPLIER SELECTION

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ABSTRACT:
Purpose:
This study aims to offer a different approach to supplier selection focused on sustainability. The evaluation of elements such as environmental impacts, social responsibility and economic efficiency together has become increasingly important today. To manage the uncertainties and missing data encountered in the decision-making process, the Grey Relational Analysis method was preferred. The aim is not only to list the alternatives but also to make the process more systematic and more understandable for the decision maker.
Study design/methodology/approach:
The proposed model is developed based on the multi-criteria decision-making approach and is based on the Grey Relationship Analysis method. Firstly, sustainability-based evaluation criteria are determined by expert opinions, then supplier alternatives are ranked by means of normalized decision matrices and relationship coefficients. A sample case study is carried out to demonstrate the applicability of the method.
Findings:
The model allows for a balanced assessment between economic, environmental and social factors. Meaningful comparisons could be made even with incomplete or uncertain data. It not only provides a ranking but also gives decision-makers an idea of where improvements are needed. The results obtained are largely in line with the sustainability goals of organizations.
Originality/value:
This study presents a new gray-based decision model for sustainable supplier selection. Thanks to its ability to consider uncertain and subjective data, it both makes a methodological contribution to literature and provides a practical way for practitioners.

KEYWORDS
Sustainable procurement, Grey Relationship Analysis, Multi-criteria decision making, Supplier evaluation

RELATED TOPICS
Sustainability in logistics and supply chains
Sourcing and outsourcing

SELECTING AI AGENTS FOR ROUTE OPTIMIZATION UNDER SUSTAINABILITY CONSTRAINTS: A MULTI-CRITERIA DECISION FRAMEWORK

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ABSTRACT:

Purpose:

This study aims to develop a structured decision-support framework for selecting an AI (Artificial Intelligence) agent suitable for route optimization within sustainable supply chain operations. By simultaneously addressing environmental, economic, and social sustainability dimensions, the framework supports balanced evaluation in AI-enabled logistics decision-making.

Study design/methodology/approach:

A hybrid multi-criteria decision-making (MCDM) framework integrating the Weighted Aggregated Sum Product Assessment (WASPAS) and TODIM (Interactive Multi-Criteria Decision Making) methods is proposed. WASPAS is first employed to aggregate performance scores across criteria using a compensatory mechanism and to generate normalized results. These outcomes are subsequently refined through TODIM, which incorporates behavioral decision characteristics such as loss aversion and risk sensitivity. Criterion weights are determined through an influence-based weighting approach that accounts for both the number of decision-makers involved and their average managerial experience, enabling a more representative reflection of stakeholder influence.

Findings:

The results demonstrate that the integrated framework yields stable and coherent rankings of AI agent alternatives. While WASPAS highlights trade-offs among sustainability criteria, TODIM captures non-compensatory and risk-aware decision tendencies. The analysis further indicates that social sustainability criteria, particularly occupational safety and ethical sourcing practices, have a growing impact on AI-based route optimization decisions.

Originality/value:

This study offers an original methodological contribution by combining influence-based weighting with a hybrid WASPAS–TODIM framework for AI agent selection under sustainability considerations. The proposed approach provides practitioners with a practical and systematic tool to support sustainable AI adoption in supply chain management.

Keywords:

Artificial Intelligence, Influence Weighting, Multi-Criteria Decision Making, Route Optimization, Sustainable Supply Chain, TODIM, WASPAS.

Related Topics:

AI Agent Evaluation, Decision Support Systems, Green Logistics, Supply Chain Automation.

LMSCM2025

AN ALGORITHM PROPOSAL FOR THE PLACEMENT OF VEHICLES OF AN ELECTRIC SCOOTER COMPANY OPERATING IN KAHRAMANMARAŞ ACCORDING TO POPULATION DENSITY

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ABSTRACT:
Purpose:
Electric scooters are a dynamic element of today's urban transport systems because they are easy to use, fast, and efficient in improving urban mobility. This study discusses how population density determines the pattern of using e-scooters; thus, an algorithmic framework that optimizes the deployment of e-scooters as a sustainable means of transport in urban areas is also proposed.
Study design/methodology/approach:
The study uses a data-driven and spatial analysis approach. Geographic analysis methods are conducted by merging census information with real-time population density estimates and e-scooter usage statistics to determine high-demand zones. An algorithmic model based on these inputs is created to optimize fleet distribution by prioritizing neighborhoods that have both a high population density and show potential for usage. The model gets its context from an application scenario of an e-scooter company operating in Kahramanmaraş.
Findings:
The study uses a data-driven and spatial analysis approach. Geographic analysis methods are conducted by merging census information with real-time population density estimates and e-scooter usage statistics to determine high-demand zones. An algorithmic model based on these inputs is created to optimize fleet distribution by prioritizing neighborhoods that have both a high population density and show potential for usage. The model gets its context from an application scenario of an e-scooter company operating in Kahramanmaraş.
Originality/value:
This study adds to the literature by presenting a population density–based algorithmic proposal for e-scooter deployment as integrated geographic analysis with urban mobility and includes a city-specific application for Kahramanmaraş. Therefore, this study generates an applicable model that is replicable for e-scooter companies and urban planners who intend to implement micro-mobility solutions in terms of sustainable urban transport strategies.
Keywords:
Algorithm, Kahramanmaraş, Population, Scooter
Related Topics:
Smart and durable city logistics and supply chains, Innovative and smart technologies in logistics and supply chains

MULTI-OBJECTIVE OPTIMIZATION OF DELIVERY TIME AND CARBON EMISSIONS IN E-COMMERCE LOGISTICS USING A PARETO-BASED GENETIC ALGORITHM

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ABSTRACT:
The rapid growth of e-commerce has significantly increased the demand for efficient and sustainable logistics operations. As consumers increasingly expect faster deliveries, logistics providers are challenged to minimize environmental impacts, particularly carbon emissions. This study presents a multi-objective optimization model that aims to simultaneously reduce delivery time and carbon emissions. A genetic algorithm (GA)-based approach is employed to solve the complex routing problem by exploring a wide range of feasible solutions and identifying optimal trade-offs between efficiency and sustainability. To support decision-making, this model incorporates Pareto-based optimization, which generates a set of non-dominated solutions reflecting different trade-offs between conflicting objectives. The use of the Pareto allows logistics managers to evaluate alternative strategies and select the most appropriate solution based on their priorities, whether focused on speed, environmental impact, or a balance of both. The findings demonstrate that genetic algorithms offer effective and adaptable solutions for enhancing sustainability in logistics. This research contributes to the growing body of knowledge in sustainable logistics by demonstrating how advanced metaheuristic algorithms can support environmentally responsible decision-making. Next studies include integrating real-time data streams, Internet of Things (IoT) technologies, and machine learning algorithms to further enhance the responsiveness, precision, and intelligence of delivery route optimization systems.

KEYWORDS
Carbon emissions, Delivery time, Genetic algorithm, Multi-objective optimization, Pareto optimization, Sustainable logistics

RELATED TOPICS
Artificial Intelligence in logistics and supply chains, Sustainability in logistics and supply chains, Green logistics and supply chain management, Innovative and smart technologies in logistics and supply chains.

LMSCM2025

EXPLORING URBAN LOGISTICS DYNAMICS: INSIGHTS FROM STAKEHOLDER PERSPECTIVES

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ABSTRACT:
Purpose:
This study aims to explore the evolving dynamics of urban logistics by examining stakeholder perspectives on last-mile delivery, sustainability, and technological transformation within urban freight systems.
Study design/methodology/approach:
A qualitative research design was adopted based on semi-structured interviews conducted with 13 industry professionals representing both public and private sector stakeholders. Following ethical approval, all interviews were recorded, transcribed using Sonix.ai, and manually verified. The data were analyzed through content analysis using MAXQDA 24 software, resulting in 121 codes grouped under 10 thematic categories.
Findings:
The findings indicate that delivery methods, sustainability considerations, and regulatory and infrastructure challenges are the most prominent themes shaping urban logistics practices. Rapid delivery expectations, artificial intelligence-based planning, and the use of electric vehicles emerge as key enablers of operational efficiency. However, regulatory gaps and insufficient infrastructure constrain the implementation of advanced solutions such as drone deliveries and urban mobility hubs. While private sector stakeholders prioritize speed, technological integration, and customer satisfaction, public sector representatives emphasize bureaucratic processes, financing constraints, and infrastructure deficiencies. Despite these differences, sustainability, strategic delivery points, and AI-driven optimization appear as common priorities.
Originality/value:
This study contributes to the urban logistics literature by providing a stakeholder-oriented perspective on the challenges and opportunities of last-mile delivery in urban contexts. The findings offer practical insights for policymakers and practitioners aiming to develop sustainable, technology-driven, and customer-oriented urban logistics frameworks.

KEYWORDS
Content Analysis, Sustainability, Last-Mile Deliveries, Urban Logistics

RELATED TOPICS
Urban life and freight distribution systems, Technology-enabled sustainable last-mile logistics

STRATEGIC INTERNATIONAL TRADE AND LOGISTICS MANAGEMENT REGARDING RECENT REGIONAL CONFLICTS IN THE MIDDLE EAST

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Abstract:
This study explores the trade and logistics implications of the ongoing tensions and conflicts in the Middle East, with a focus on how these developments influence the global fertilizer sector. The Israel-Iran conflict is not only a geopolitical or military issue but also has significant economic and sectoral consequences. While the global spotlight has been on energy prices and supply risks in the Strait of Hormuz, less attention has been paid to the impact on fertilizer trade. Both Iran and Israel are major global players in fertilizer exports. Iran ranks among the top three urea exporters, shipping approximately 5 million tons of urea and 4.5 million tons of ammonia annually. Israel exports about 4.5 million tons of potassium fertilizer, making it the fourth-largest exporter in that category. The conflict has led to production halts in both countries, directly affecting other producers such as Egypt, Qatar, and Saudi Arabia. Egypt, heavily dependent on Israeli gas, suspended operations, while Iran shut down seven major urea and ammonia plants. These disruptions have increased freight and production costs, caused delays in supply chains, and driven up prices globally. Countries like India, Brazil, and Bangladesh have turned to early ordering and stockpiling in response. Turkey, which is 90% dependent on imported fertilizer raw materials, is particularly vulnerable, sourcing primarily from Oman, China, Russia, Egypt, Turkmenistan, and Iran. The limited domestic supply and rising costs are pressing the Turkish fertilizer sector to seek alternative strategies. Artificial intelligence is also anticipated to be helpful in predicting problems and creating backup plans for the commerce and logistics of fertilizer. The short-term effects of this crisis are evaluated in this study, with more comprehensive analysis to follow during the research process.

KEYWORDS
ammonia production, fertilizer supply chain, geopolitical risk, Iran-Israel conflict, potash export, urea prices

RELATED TOPICS
Agricultural Trade and Food Security, Supply Chain Disruption and Resilience

MODELING COMPANY SIZE SCORE: APPLICATION IN THE LOGISTICS SECTOR

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ABSTRACT:

Purpose;

The logistics sector is a constantly evolving service industry characterized by high operational complexity and intense competitive pressure. Within this structure, accurately measuring company size is critical for strategic planning, partnerships, competitive analysis, and particularly for effective human resource management and remuneration practices. However, traditional size indicators such as sales revenue and number of employees fail to fully capture the multidimensional nature of logistics firms, which are generally classified as micro, small, medium, or large enterprises.

This study introduces the Company Size Score (CSS) model, developed to evaluate the scale of logistics companies from a more comprehensive and multidimensional perspective. The model incorporates various criteria including sales revenue, financial balance sheet value, organizational structure, vehicle fleet size, warehouse capacity, number of regions served, level of digitalization, shipment volume, number of employees, sustainability practices, and customer diversity. These criteria are weighted using multi-criteria decision-making (MCDM) techniques and converted into a composite score. The model establishes a structured basis for employment decisions, appointments, training, and remuneration systems.

Findings;

The findings indicate that company size in the logistics sector cannot be adequately explained by physical capacity indicators alone. Instead, size becomes meaningful when strategic, technological, and operational dimensions are evaluated simultaneously. The CSS model enables a more objective and nuanced classification of logistics companies, allowing for clearer differentiation among firms with similar traditional size indicators but differing operational and strategic capabilities.

Originality;

This study is original in proposing an integrated and quantitative scoring model specifically tailored to the logistics sector. Unlike conventional classification approaches, the CSS model combines financial, operational, technological, and This study is original in proposing an integrated and quantitative scoring model specifically tailored to the logistics sector. Unlike conventional classification approaches, the CSS model combines financial, operational, technological, and sustainability-related criteria within a unified framework. By offering a practical and objective measurement tool for sectoral comparison, the study contributes to the academic literature and provides decision support for logistics managers and human resource professionals.

KEYWORDS
Logistics sector, Company Size Score, Multi-criteria decision-making (MCDM), Strategic planning

RELATED TOPICS
Digitalization, Sustainability practices, Warehouse capacity, Shipment volume

SUPPLY CHAIN AGILITY IN DISASTER MANAGEMENT

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ABSTRACT:
Purpose:
A common feature of all natural or man-made disasters is that they have negative social, economic, cultural, and physical consequences that disrupt normal order and functioning. This situation necessitates the planned, coordinated, and effective implementation of disaster relief efforts involving products, information, and services to assist those affected by disasters. In this regard, supply chain management has gained great importance as one of the most critical aspects of disaster relief efforts. The planning, coordination, and management of supply chain activities are essential before, during, and after a disaster for successful crisis management. In particular, Effective and efficient disaster supply chain management enables humanitarian organizations to match high-priority needs with available materials in a short period of time, ensuring the best use of resources under limited financial constraints. The entire logistics process that ensures the right goods, services, and information are delivered to the right place at the right time after a disaster is called the "disaster supply chain." Challenges such as damage to infrastructure (roads, ports, bridges), lack of information, security threats, insufficient resources, and lack of coordination between stakeholders are encountered. Environmental challenges (such as weather conditions) can also affect the process.
This study aims to highlight the importance of supply chain agility in disaster management. Agility enables fast, flexible, and effective aid delivery in times of crisis and plays a critical role in the success of post-disaster logistics processes.
Study design/methodology/approach:
The study was prepared using a qualitative approach based on literature review and case studies.
Findings:
The Haiti Earthquake (2010), the Covid-19 pandemic (2020), the Japan Tōhoku Earthquake and Tsunami (2011), and the Australian Bushfires (2019-2020) are examined as case studies. These cases reflect different dimensions of agility in disaster supply chains (structural, operational, flexibility, speed, responsiveness, visibility). Findings show that agility is achieved through rapid adaptation, alternative logistics solutions, technology use, and stakeholder collaboration. Alternative warehouses and routes in Haiti, cross-sector production transformations during Covid-19, a multi-layered supply chain approach in Japan, and resource sharing in Australia are examples of different applications of agility.

Originality/value:
The study provides a comprehensive framework by comparatively analyzing disaster supply chain agility in different crisis scenarios, bringing together fragmented information found in the literature. Thus, it contributes conceptually from an academic perspective and offers practical insights to practitioners regarding logistics planning and coordination in crisis management.

KEYWORDS
Disaster management, disaster supply chain, humanitarian logistics, supply chain agility.

RELATED TOPICS
Emergencies and crisis logistics and supply chains, Humanitarian logistics and supply chains.

THEMATIC ANALYSIS OF THE LAST DECADE IN SUSTAINABLE SUPPLY CHAIN MANAGEMENT LITERATURE: CONCEPTUAL DEVELOPMENTS AND FUTURE RESEARCH DIRECTIONS

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ABSTRACT:
Purpose:
Sustainability and supply chain management have emerged as two increasingly interconnected research domains within the academic literature over the past decade. This study aims to conduct a thematic analysis of scholarly publications in the field of sustainable supply chain management (SSCM) published between 2014 and 2024. A total of 17,896 academic articles indexed in the Web of Science database were examined, and a bibliometric analysis was carried out using the VOSviewer software based on keyword co-occurrence mapping.
Study design/methodology/approach:
The results reveal that "sustainable supply chain management" occupies a central position within the academic discourse, with closely associated concepts such as sustainability, supply chain management, stakeholder theory, green supply chain management, and corporate social responsibility clustering around it. Furthermore, emerging themes such as social sustainability, climate change, circular economy, information processing theory, and big data analytics have gained notable prominence in recent years.
Findings:
One of the key findings of the study is the sectoral differentiation of sustainability-related subdimensions particularly in areas such as the automotive, food, and energy industries highlighting the varied contextual applications of circular economy, social responsibility, and climate change. Additionally, the rise of data-driven approaches and multi-tier supply chains signals new avenues for future research. The increasing academic attention to the UN Sustainable Development Goals (SDGs) further demonstrates the alignment between global sustainability agendas and scholarly inquiry.
Originality/value:
This thematic analysis provides a comprehensive overview of current trends, emerging topics, and research gaps within the SSCM literature, offering valuable insights for both researchers and practitioners aiming to understand and contribute to the strategic evolution of sustainable supply chains.

KEYWORDS
Bibliometric Analysis, Circular Economy, Climate Change, MCDM, Sustainable Supply Chain Management
RELATED TOPICS
Sustainable Supply Chain, MCDM

ENRICHMENT OF DIGITAL TWINS WITH GENERATIVE AI IN SUPPLY CHAIN 4.0 PROCESSES

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ABSTRACT:
Purpose:
The aim of this study is to investigate the integration of Generative Artificial Intelligence (GenAI) and digital twins in the context of Supply Chain 4.0. The study evaluates their potential to improve predictive analytics, enhance decision support processes and optimise system learning. It also aims to present a conceptual model for the development of next-generation digital twin architectures for sustainable and resilient supply chain management.
Study design/methodology/approach:
The study takes a conceptual approach by examining the existing literature on digital twins and the integration of GenAI. The study proposes a model that shows how the extension of digital twins with GenAI can improve processes in the supply chain and presents example scenarios from different industries. It focuses on key areas such as scenario generation, predictive analytics and real-time decision support systems.
Findings:
The study found that the integration of GenAI and digital twins significantly increases the flexibility, resilience and sustainability of supply chains. When digital twins are integrated with GenAI, supply chain systems become more adaptable and significantly change both reactive and proactive decision-making processes. The results suggest that this integration will play a critical role in future decision support systems.
Originality/value:
This study makes a significant contribution by filling a gap in the literature where no systematic review of the integration of digital twins with GenAI has been conducted. It also provides a roadmap for the development of next-generation digital twin architectures for sustainable and resilient supply chains.

KEYWORDS
Digital twins, generative artificial intelligence, predictive analytics, supply chain 4.0, supply chain optimization

RELATED TOPICS
Supply Chain 4.0, Generative Artificial Intelligence

A COMPREHENSIVE LITERATURE REVIEW ON THE LOGISTICS PERFORMANCE INDEX

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ABSTRACT:

Purpose:

This study aims to provide a comprehensive literature analysis of the academic research focused on the Logistics Performance Index (LPI) published by the World Bank. It systematically examines publication trends, methodological approaches, thematic focus, and the geographic scope of 68 articles published between 2008 and 2025 to guide future researchers and policy-oriented studies.

Findings:

The analysis reveals a significant methodological shift over the years. While early studies primarily utilized econometric and gravity models to establish the link between logistics and trade, recent research (especially after 2020) shows a dominant trend toward multi-criteria decision-making (MCDM) methods, such as Entropy, TOPSIS, and hybrid models. Thematic focus has also evolved from basic performance assessments to integrated topics like sustainability, digitalization, and crisis resilience. Geographically, research is heavily concentrated on OECD, G20, and EU countries, often overlooking top-ranked performers like Singapore that do not belong to these specific groups.

Originality/Value:

This study is significant as it reflects on the general state of research regarding the only index that measures global logistics performance. By identifying the increasing move toward methodological objectivity—such as the World Bank's recent inclusion of external data providers—and highlighting the thematic diversification in the field, this review provides a valuable foundation for understanding the evolution of global logistics evaluation.

KEYWORDS

Logistics Performance, Logistics Performance Index, LPI

RELATED TOPİCS

Logistics Management, Transportation and Logistics

BRAZIL AS POTENTIAL LOGISTICS HUB FOR THE GLOBAL SUPPLY CHAIN

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ABSTRACT:

The global supply chain challenges in the form of military conflicts, pandemics and energy crises encourage managers to relocate operations. The purpose of this paper is to present Brazil as a developing hub focusing on logistics performance as an essential factor encouraging investment and trade cooperation. The logistic performance index shows perceived progress in Brazil, and the analysis of various sources with the national Logistics Plan among them brings a conclusion aiming towards key areas to improve. The most pronounced is customs policy. The outdated regulations and administrative hindrances make international logistics operations less efficient. There is a need to enhance legal solutions and technical equipment, helping to secure and speed up operations. Another important factor is logistics infrastructure, where spending has decreased over the decade. There are plans to improve this factor as the one where state responsibility is unavoidable.

KEYWORDS

International logistics, transport, logistic performance, trade, infrastructure.

RELATED TOPİCS

Logistics management, Logistics corridors and centers.

A BIBLIOMETRIC STUDY ON BLOCKCHAIN AND DATA SECURITY

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ABSTRACT:
Purpose:
The aim of this study is to evaluate the position of blockchain technology in the field of data security within the academic literature and to examine the patterns and current trends of scholarly publications related to key concepts through the bibliometric analysis method. In this way, it is intended to understand the theoretical development in the specified field, contribute to the body of knowledge, and guide future studies.
Study design/methodology/approach:
On June 17, 2025, the keywords "Blockchain" and "Data Security" were searched in the Web of Science (WoS) database using the "topic" filter. As a result of the search, 2,104 studies were identified. Duplicates and letters to the editor were excluded, and data consisting of 2,078 studies were obtained. The dataset was analyzed using the VOSviewer software.
Findings:
The bibliometric analysis reveals the evolving structure of blockchain research in the context of data security, highlighting dominant research themes, influential publication clusters, and emerging interdisciplinary application areas within the literature.
Originality/value:
This study, which reveals the position of blockchain technology in the scientific literature on data security through a bibliometric approach, highlights the existing gaps in the literature and maps the interdisciplinary areas of application. Thus, it provides a concise knowledge base related to key concepts while aiming to guide future research and offer a substantive contribution to the field. This study also provides insights into how blockchain-based data security solutions can enhance transparency, traceability, and trust across logistics and supply chain systems.

KEYWORDS
Blockchain, Data Security, Bibliometric Analysis, VOSviewer Management Information Systems.

RELATED TOPİCS
Innovation and technology management.

LMSCM2025

DARK FACTORIES AND AUTONOMOUS LOGISTICS: A SUSTAINABILITY-ORIENTED ASSESSMENT

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ABSTRACT:
Purpose:
This paper aims to assess the sustainable consequences of two new technologies in the field of supply chain management, dark factories and autonomous logistics systems. It emphasizes how, through these technology applications combined with generative artificial intelligence (GenAI), environmentally friendly, economically viable, and socially sustainable supply chains can be created within Industry 5.0.
Study design/methodology/approach:
A qualitative research methodology is applied through literature review and some manufacturing and logistics industry case studies. Review of critical sustainability metrics such as energy used, carbon output, production yield, people impact, and values. The potential of GenAI in production planning, routing optimization, and predictive decision-making is also discussed.
Findings:
This study has shown that future GenAI-powered dark manufacturing and autonomous logistics systems can enhance operational sustainability when combined with a suitable strategy and governance. Such technologies minimize wastage of resources and utilize energy more efficiently, contributing to supply network responsiveness. Yet, issues such as labour displacement, data ethics, and technology reliance persist and must be tackled for an inclusive and durable implementation.
Originality/value:
This study provides a combination of views on the future role and the contribution of generative AI to the sustainable supply chain's future advancement through enhanced automation. The study reveals strategic opportunities in integrating dark factories and autonomous logistics to achieve sustainability goals. It develops futuristic conceptual and policy implications to directive academics, practitioners, and policymakers in the AI, manufacturing, and sustainability domains.

KEYWORDS
Autonomous Logistics, Dark Factory, Generative Artificial Intelligence, Industry 5.0, Sustainability

RELATED TOPİCS
Autonomous vehicles in logistics and supply chains, Sustainability in logistics and supply chains

INTRODUCTION

Dark or "lights-out" factories are manufacturing facilities that operate entirely using automated processes with little or no human intervention. In a dark factory, all production processes are controlled by robots, machines, and software to produce products without humans. The term "lights-out" refers to the fact that these factories can operate without human presence, and the lights can be turned off while the factory continues operating (Gisi, 2024).

Dark factories are more common in industries requiring high levels of precision and efficiency, such as electronics, medical devices, and automotive component manufacturing. Able to operate continuously around the clock with minimal downtime, they can produce products much faster than traditional factories (Ivanov, 2021). These factories, which we call the factories of the future, are expected to be highly automated and efficient, creating fully integrated and optimized production processes through artificial intelligence, machine learning, and the internet of things (Lu, 2017). Using high automation, in turn, leads to increased productivity, lower costs, and faster delivery times, enabling the production of goods on demand and reducing waste (Kusiak, 2018). However, establishing a dark factory requires significant investments in automation technology and infrastructure, potentially impacting employment (Brynjolfsson & McAfee, 2014).

An autonomous logistics system is a sophisticated integration of technologies and processes that enables logistics operations to operate with minimal human intervention. These systems are designed to increase logistics efficiency, accuracy, and safety by leveraging advanced robotics, communication, and control mechanisms. Key components of such systems include autonomous vehicles, intelligent recognition devices, and dynamic modeling techniques, all of which contribute to a seamless logistics process (Nitsche, 2021).

Companies' digital transition processes are an important issue for implementing dark factories in developing countries, which brings several advantages and disadvantages. This shift requires not only the deployment of advanced technologies but also the redesign of socio-technical systems to ensure inclusive value creation. As such, digital transition should be guided by human-centric principles to avoid the pitfalls of technocentric approaches seen in early Industry 4.0 implementations (Neumann et al., 2021). When Industry 4.0 focuses on technology and profit, neglecting stakeholder prosperity, Industry 5.0 emphasizes human-centric, resilient, and sustainable systems (Grosse et al., 2023).

Incorporating dark factories and autonomous logistics systems into contemporary production and supply chains offers substantial sustainability benefits while introducing critical complexities. From an environmental perspective, these technologies enhance resource efficiency, minimize operational waste, and reduce energy consumption through data-driven precision. Autonomous logistics, for example, can streamline delivery routes, curbing fuel consumption and lowering carbon emissions—a key advantage in mitigating climate impact (Winkelhaus & Grosse, 2020).

However, the sustainability outcomes of these systems depend heavily on their design, implementation, and governance. While automation can optimize production, it often relies on energy-intensive infrastructure, which may balance potential ecological gains if powered by non-renewable sources (Beltrami et al., 2021). Beyond environmental concerns, the shift toward full automation poses socioeconomic challenges, including workforce displacement, widening digital divides, and weakened labor market resilience—factors that undermine the social pillars of sustainability (Brynjolfsson & McAfee, 2014; Neumann et al., 2021).

Thus, these innovations present a paradox: they promise to advance environmental and economic sustainability when integrated with long-term planning and renewable energy, yet they risk deepening societal inequities if deployed without inclusive policies (Ivanov, 2023). Therefore, a comprehensive evaluation of dark factories and autonomous logistics must adopt a multidimensional lens, considering ecological, economic, and social consequences to ensure balanced and equitable progress.

This study aims to examine the contribution of dark factories and autonomous logistics systems with generative artificial intelligence to supply chain processes and to investigate their environmental, economic, and social dimensions from a sustainability perspective. The study will conduct examinations of the key players in the dark factories market using various evaluation criteria.

LITERATURE REVIEW

Technological Foundations

The theoretical foundations for dark factories and autonomous logistics are based on core Industry 5.0 technologies. Artificial Intelligence (AI) and Machine Learning (ML) algorithms enable predictive maintenance, quality checking, and real-time process optimization (Javaid et al., 2022). Internet of Things (IoT) sensors continuously monitor equipment health, environmental conditions, and product quality, creating a comprehensive data system enabling autonomous decision-making (Ruth et al., 2024).

Cyber-Physical Systems (CPS) support these implementations, linking physical manufacturing operations and computerized control systems (Bonci et al., 2024). These systems facilitate real-time monitoring and parameter adjustment for easy dark factory operation without immediate human intervention. Automation and robotics technologies manage material handling, assembly, and quality inspection with precision levels usually greater than human capabilities (Popescu et al., 2024). Nevertheless, the high degree of interconnection provided by Industry 5.0 systems presents exposure to cyberattack, risk of production disruption, and compromised product quality (Kazi et al., 2024).

Digital Twin technology creates virtual models of physical systems to facilitate simulation, optimization, and predictive analytics of manufacturing processes (You, 2024). With no need for human direct observation, Digital Twins provide critical visibility into operational performance and potential failure. While dark factories excel in standardized mass production, they may indicate lower flexibility to respond to rapid product change or customization needs traditionally accommodated through human involvement.

Autonomous Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs) are the physical enablers of autonomous logistics networks. They manage material flow, inventory management, and order picking with minimal human intervention (Popescu et al., 2024). With warehouse management systems, they optimize routing and scheduling to reduce energy consumption and operation waste. However, the complexity of integrating many new technologies brings new challenges like expertise requirements and unanticipated system interactions that may lead to operating malfunction (Rahmani et al., 2024).

Sustainability and Environmental Impacts

Dark factories and autonomous logistics are of high sustainability value in terms of energy efficiency, resource optimization, and waste reduction. Energy efficiency is achieved through smart lighting systems (or lack thereof), reduced heating and cooling needs due to the absence of human workers, and smart energy management software that automatically adjusts energy consumption based on production needs (Dahmani, 2024). Empirical evidence shows that Industry 5.0 technologies reduce energy usage by 13.41% and material consumption by 13.04% compared to conventional manufacturing systems (Bonci et al., 2024).

Smart Energy Management systems enable real-time observation and dynamic power use management of manufacturing processes (Kluczek & Buczacki, 2023). The system lowers peak demand charges, coordinates with renewable energy supply, applies predictive maintenance to prevent inefficient equipment failure, and schedules production for optimal conformance with sustainable energy availability.

Besides energy saving, dark factories also contribute to carbon footprint reduction with optimized routing algorithms in autonomous logistics, reducing emissions from transportation, minimizing wastage of resources by precise process control, and enhancing equipment lifespan through predictive maintenance (Bag et al., 2023). Complete environmental audits also reveal additional benefits in reduced water consumption, lower use of chemicals, and less waste generation (Shabur, 2024).

Closed-loop water cycles and monitoring technologies reduce water usage in transportation, cooling, and cleaning processes. At the same time, the absence of access to sanitation facilities for workers further reduces consumption. Precision dosing technology in automatic production limits excessive use of chemicals, though with lower wastage of the environment and operations. Nevertheless, life cycle assessments are necessary to account for operational benefits and life environmental costs between manufacturing, installation, and later dismantling of automation equipment (Liu et al., 2024).

Occupational Health and Safety Implications

The contribution of dark factories to labor safety is significant. Occupational health dangers are greatly reduced by eliminating human workers from toxic, hot, or heavy machinery environments. IOT monitoring: IoT-based monitoring and AI-based predictive notifications notify of any unsafe conditions in advance, and automatic shutdown can avoid risks.
In logistics, automation support can also aid in preventing musculoskeletal disorders by taking over repetitive and physically challenging activities, such as heavy lifting, manual handling of loads, or material holding. While traditional risks decline, new challenges arise: maintenance staff must interact with complex robotic and AI systems, necessitating specialized safety training and adaptation to emerging risk categories (Kazi et al., 2024).

Economic Considerations

The economic viability of dark factories relies on the production volume, labor costs, energy costs, and the complexity of the process. Those industries with high labour costs and dangerous work environments or that require exacting quality standards experience a quicker return on their investment in automation. It is a costly way to get started (since startup capital is high), but, in the long run, it can be a competitive way to operate.
The major economic benefits are direct labor cost reduction and the capacity for interruption-free 24/7 production. Further savings are achieved through predictive maintenance, resulting in reduced scheduled and unscheduled maintenance costs and better quality, curtailing rework and warranty claims (Jasiulewicz–Kaczmarek, 2024). The stated energy savings of 13.41% directly translate into cost savings (Bonci et al., 2024).
However, high initial costs prevent it from being used, for example, by SMEs. Furthermore, automation-based job displacement poses complex social issues; it will require consistent requalification of workers and social support to manage the risks of unemployment. Lastly, a lack of available technicians and engineers with the requisite skills in robotics, AI, and systems integration might hinder widespread adoption.

ORIGINALITY OF THE STUDY

Autonomous Logistics and Supply Chain Integration

Autonomous logistics utilizes transportation, storage, and distribution solutions powered by artificial intelligence, sensors, robotic systems, and IoT, without human intervention. Various monitoring technologies enable real-time tracking, route optimization, demand forecasting, load optimization, and more, enabling workforce optimization, fuel savings, resource efficiency, and more.
Supply Chain Integration (SCI) is the coordination and collaboration among various stakeholders, processes, and systems within a supply chain ecosystem. The primary focus of SCI is to achieve a seamless flow of information, real-time visibility, and efficient decision-making. Achieving this requires combining internal processes and integrating external partners, such as suppliers, manufacturers, distributors, and customers. In dark factories, SCI becomes even more critical as it synchronizes and optimizes production processes, inventory management, and logistics operations. The key significance of SCI is detailed next (Mathivathanan & Kirubanandan, 2024):

- Seamless flow of information

- Improved coordination and collaboration
- Enhanced responsiveness and agility
- Optimal resource utilization
- Continuous improvement and innovation

Therefore, SCI is pivotal in facilitating the seamless exchange of information, thereby enhancing coordination and collaboration among diverse stakeholders. In addition, SCI contributes to developing responsive and agile supply chains that optimize resource utilization while fostering continuous improvement through innovation, an essential condition for maintaining competitiveness in dynamic market environments.

Also, the managers face some challenges in facilitating seamless SCI in dark factories. From a manufacturing perspective, SCI is generally faced with several traditional challenges that can hinder the smooth flow of information, coordination, and collaboration among stakeholders. Some of the challenges are listed below:

- Siloed information within departments checks data flow, delays real-time visibility, and creates inconsistencies, leading to uncertainties, errors, and inefficiency (Sjödin et al., 2018).
- Outdated software, hardware, communication technologies, and a lack of standardization and interoperability lead to data incompatibility, hindering the smooth exchange of information (O'Donovan et al., 2016).
- Incomplete, outdated, or inconsistent data from traditional systems impacts decision-making and planning processes in the supply chain (Illa & Padhi, 2018).
- Employees accustomed to established processes and working methods resist changes and hinder effective integration (Sjödin et al., 2018).
- Establishing trust and promoting collaborative relationships are major barriers to effective integration (Cooke, 2021).
- A major challenge for successful integration is ensuring robust cybersecurity, data encryption, access controls, and compliance with privacy regulations (Ghobakhloo, 2020).
- Traditional manufacturing environments face challenges aligning their systems, processes, and data-sharing capabilities with integration initiatives (Davis et al., 2012).

Adaptive Supply Chain Management and Dark Factories

Adaptive supply chain (ASC) management highlights the capacity of supply chains to anticipate and effectively respond to rapidly changing market dynamics, developing customer expectations, and unexpected disruptions (Ivanov et al., 2012). Beyond incorporating agile practices, ASCs combine flexibility through advanced digital technologies and real-time data analytics (Urciuoli & Hintsa, 2017). In this sense, ASCs can be understood as digitally transformed manufacturing and logistics systems supported by IoT, artificial intelligence, and automation. Central to their design is an emphasis on resilience and responsiveness, enabling organizations to navigate and mitigate unexpected market challenges.

Ivanov et al. (2010) conceptualize adaptive supply chains (ASCs) as networked organizational systems in which multiple enterprises collaborate and coordinate across the entire value chain and product life cycle. This collaboration involves acquiring raw materials, transforming them into final products, delivering goods to retailers, designing new products, and providing post-production services. Moreover, ASCs incorporate contemporary concepts and advanced technologies to enhance responsiveness, flexibility, resilience, sustainability, and cost efficiency. The ultimate objective of this integration is to improve customer satisfaction while simultaneously reducing operational costs, thereby strengthening overall supply chain profitability. Thus, ASCs can be characterized as complex, multi-structured systems capable of adjusting to dynamic market conditions, evolving operational environments, and internal organizational changes. This adaptability is primarily driven by advanced information technologies, such as the IoT and AI, which enable real-time visibility, predictive insights, and enhanced decision-making across the supply chain.

Some key emerging trends in ASC integration for smart focus on leveraging advanced technologies, data-driven insights, and collaborative approaches to enable agile, responsive, and efficient supply chains are presented below:

- AI algorithms process data collected from IoT devices, sensors, and other digital sources to identify patterns, trends, and anomalies. Building on these insights, ML models support real-time decision-making by forecasting demand, optimizing inventory levels, and improving general supply chain responsiveness (Sharp et al., 2018).
- The use of advanced data analytics tools and techniques to derive actionable insights from large and heterogeneous datasets enhances demand forecasting, improves supply chain visibility, maintains risk management, and supports more knowledgeable decision-making (Tiwari et al., 2018).
- IoT plays a crucial role in ASC integration by enabling real-time data collection, seamless connectivity, and enhanced visibility through interconnected devices, sensors, and digital systems (Rana et al., 2022).
- Blockchain technology has emerged as a prominent area of research within ASC integration, as it enables secure and transparent data sharing across the network. By ensuring traceability, origin verification, and real-time information exchange, blockchain enhances visibility and accountability throughout the supply chain. Furthermore, smart contracts embedded within blockchain platforms automate and simplify operational processes, thereby promoting trust, improving efficiency, and facilitating seamless collaboration among stakeholders (Bhaskar et al., 2022).
- Collaboration among supply chain partners through digital platforms and cooperative networks is an emerging trend in ASC integration (Herczeg et al., 2018).
- Sustainable practices and circular economy research have delved into ASC integration (Cioffi et al., 2020).
- AI-driven predictive maintenance and asset optimization, supported by advanced analytics and IoT sensors, enable continuous real-time monitoring of equipment health and performance while proactively identifying maintenance requirements (Corallo et al., 2022).

Current ASC integration directions in smart factories are about creating agile, robust, and customer-focused supply networks. Blockchain technologies enable more transparency, traceability, security, and collaboration along the supply chain. In parallel, edge computing can process data and make decisions in real-time at the network edge, improving operational efficiency, security, and predictability. The convergence of these technologies drives ASC integration, and dark factories can produce supply chains that are not only responsive and efficient but also transparent and agile to react to the dynamic market environment.

KEY PLAYERS IN THE DARK FACTORIES MARKET

The key players in the dark factories market include FANUC CORPORATION; Amazon.com, Inc.; Xiaomi.; Hon Hai Precision Industry Co., Ltd.; Simplifyber, Inc.; DeepHawk Inc.; Xaba Inc.; A3D Manufacturing; Geofabrica Inc.; STILRIDE; BYD Company Ltd (Grand View Research, GVR, 2024).

FANUC CORPORATION

FANUC Corporation is a leading global factory automation and industrial robotics provider, with core expertise in CNC systems, robotic arms, and automated machining technologies. The company has played a pivotal role in advancing the concept of dark factories by embedding artificial intelligence, machine learning, and advanced sensor technologies into its automation solutions. Through these innovations, FANUC enables the development of fully autonomous production lines capable of operating with minimal human intervention. Its focus on precision, reliability, and uninterrupted operation positions the company as a key facilitator in the global transition toward lights-out manufacturing, particularly within automotive, electronics, and heavy machinery industries (GVR, 2024).

The Fanuc sustainability mark, consisting of a "tree leaf" and an "infinity" symbol, represents the commitment of the corporation to creating a sustainable society. FANUC's two perspectives on sustainability are "energy saving and carbon neutrality" and "SDGs" (FANUC Sustainability Report, 2024). Table 1 shows that the use of recycled waste at FANUC usually increased between 2019 and 2023, the use of renewable energy remained stable, except for 2023, and there was a decrease in greenhouse gas emissions, especially in the last three years. Also, within Scope 1 and Scope 2 (market-based) greenhouse gas emissions (tCO2e), the emission change between the 2023 and 2024 fiscal years was realized as -4.024 (FANUC GHG Verification Report, 2025).

Table 1: FANUC Corporation Sustainability Report (FANUC ESG Data Book, 2024)

FANUC	2019	2020	2021	2022	2023
Waste cycled (t)	1,960	2,507	3,524	3,721	3,394
Renewable energy used (GJ)	375	386	385	375	73,637
GHG emission Scope 2 (t-CO2e)	91,639	107,208	92,625	77,296	69,392

Amazon.com, Inc.

Amazon is a global company with more than 1.5 million full- and part-time employees worldwide and operations in Africa, Asia-Pacific, Europe, Latin America, the Middle East, and North America. Amazon has invested extensively in automation, robotics, and AI-driven logistics. The company has been instrumental in advancing the concept of dark warehouses—highly automated fulfillment centers that function with limited human involvement. Through its subsidiary Amazon Robotics, the firm deploys thousands of robots and intelligent systems to optimize critical warehouse operations, including sorting, picking, and packing. By prioritizing operational efficiency, leveraging advanced data analytics, and integrating its logistics systems with Amazon Web Services (AWS), Amazon has developed a dark factory model capable of seamless, large-scale operation. Also, they set bold, long-term aspirations, such as The Climate Pledge—their goal to reach net-zero carbon emissions across our global operations by 2040—and create strategic, actionable plans to achieve them.

The landfill diversion rate, which is the measure of waste successfully diverted for recycling and not sent to landfills by incineration with energy recovery, was 85% in 2024, 84% in 2023, and 82% in 2022. In 2024, AWS had 24 data centers using recycled water for cooling and is working to quadruple the number of data centers using recycled water by 2030. AWS has agreements with seven utilities, enabling more than 4 billion liters of fresh water to be preserved for community use. As of the end of 2024, five data centers have operational rainwater capture systems in place, reducing their demand on community water resources and the adverse effects of stormwater runoff, a leading source of water pollution globally. Also, Table 2 shows that the emission from direct operations (Scope 1) is increasing, the emission from purchased electricity (Scope 2) is decreasing, and the emission from indirect sources (Scope 3) is almost stable.

Table 2: Amazon.com Inc. Emission Report (Amazon Sustainability Report, 2024)

Amazon.com Inc.	2019	2020	2021	2022	2023	2024
Emission Scope 1 (t-CO2e)	5.76	9.62	12.11	13.02	14.22	15.13
Emission Scope 2 (t-CO2e)	5.50	5.27	4.07	3.06	2.76	2.80
Emission Scope 3 (t-CO2e)	39.91	45.75	55.36	49.02	47.40	50.32

Xiaomi

In 2024, Xiaomi Smart Factory and Xiaomi EV Factory were officially completed and put into operation, and the construction of Xiaomi Smart Home Appliance Factory commenced. All three factories extensively use industrial internet and AI technologies to achieve efficient, environmentally friendly, and sustainable production models through smart manufacturing processes. Xiaomi's Smart Factory, underpinned by a high proportion of self-developed hardware and software alongside digitalized production systems, has achieved full automation across key manufacturing processes. By deploying advanced technologies such as flexible production lines, automated logistics, and integrated cloud–edge–device control, the facility has reached an automation rate of 81% on its production lines—well above the industry average. In logistics management, the factory integrates equipment with the Xiaomi Hyper Smart Manufacturing Platform, enabling autonomous functions including automatic material requests, dynamic task allocation for equipment movement, and real-time inventory alerts.

Table 3: Xiaomi Key Environmental Indicators (Xiaomi ESG Report, 2024)

Xiaomi	2022	2023	2024
Emission Scope 1 (t-CO2e)	7.122	12.252	19.490
Emission Scope 2 (t-CO2e)	78.620	104.470	78.396
Total GHG Emissions (t-CO2e)	85.742	116.722	97.887

Table 3 indicates that the emission from Scope 1 is increasing, the emission from Scope 2 is almost stable except for 2023, and total GHG emissions tend to decrease.

Hon Hai Precision Industry Co. Ltd.

In 2024, Hon Hai Group advanced the digital transformation of supply chain ESG management by introducing innovative governance mechanisms and implementing fully digital ESG evaluations for its suppliers. These assessments covered key dimensions such as green product development, net-zero emissions, and zero-waste initiatives, with corresponding advisory programs to support supplier compliance. Concurrently, the company provided targeted guidance to suppliers on carbon and waste reduction, promoted the exclusive use of renewable energy in producing Foxconn products, and achieved Zero Waste to Landfill certification. Collectively, these measures contributed to measurable reductions in both carbon emissions and waste across the supply chain (Supplier Responsibility Report, 2024). According to its most recent annual sustainability report, Hon Hai Precision Industry Co., a Taiwan-based manufacturing conglomerate, achieved a renewable energy utilization rate of 67.38 percent in 2024. This figure surpasses the company's target of exceeding 50 percent renewable energy use by 2030, underscoring its accelerated progress toward long-term sustainability commitments (Focus Taiwan, 2025). Table 4 declared that the emissions are decreasing.

Table 4: Hon Hai Precision Industry Co. Ltd. Emissions (Sustainability Report, 2023)

Hon Hai	2022	2023
Emission Scope 1 (t-CO2e)	222.295	158.108
Emission Scope 2 (t-CO2e)	5.535.324	2.421.127
Total GHG Emissions (t-CO2e)	5.757.619	2.579.235

Simplifyber Inc.

Simplifyber, founded in 2020 and headquartered in New York City, specializes in sustainable textiles and advanced 3D manufacturing processes. Its core innovation lies in a cellulose-based liquid material that enables new applications of natural fibers beyond traditional methods. This approach allows fabrics to be produced additively—without spinning, weaving, cutting, or sewing—while offering scalability not previously achieved within the sustainable materials sector. After all, their manufacturing process cuts out 60% of the steps of traditional manufacturing. So, they produce 23 times more garments with 88% fewer workers and 96% fewer machines. Finally, 23 billion tons of plastic, 448 million tons of CO2e, and 3 million tons of material waste are reduced yearly (Simplifyber, 2025).

Deephawk Inc.

DeepHawk, founded in France in 2020 as a seed-stage company, specializes in AI-powered visual quality control solutions for manufacturing. Its technology is designed to deliver superior defect detection, accelerated production times, and adaptability across diverse vision systems and industries, including automotive, aerospace, and battery manufacturing (Tracxn, 2025). DeepHawk's software can identify defects as small as a single pixel in just 15 milliseconds by analyzing product images directly on production lines. The system also demonstrates a significant learning advantage over conventional AI models, requiring only 30 minutes of training compared to several weeks, while maintaining a high degree of flexibility. DeepHawk's platform can support various product categories (e.g., mechanical, automotive, and electronics) and imaging modalities (including multi-view, still and video, visible spectrum, X-ray, infrared, and microscopic). Operating fully on-premise, the solution eliminates reliance on external connections, enhancing data security. Designed as a "frugal AI," the system also minimizes computing resource requirements, reducing its carbon footprint by approximately 375 times compared to traditional models. Launched commercially in 2023, DeepHawk's solution has already been deployed in two Stellantis factories and is undergoing trials with ten additional clients across Europe and North America. The company's U.S. subsidiary, headquartered in Los Gatos, California, extends operations to the United States, Canada, and Mexico (Business France, 2025).

Xaba Inc.

Founded in 2022 and headquartered in Toronto, Canada, Xaba develops industrial AI-driven control systems to enhance automation performance. The company's technology offers substantial improvements over conventional software solutions, including deployment speeds up to 40 times faster, a tenfold increase in accuracy and repeatability with standard robotics, and a 90 percent reduction in downtime through real-world point cloud data. Moreover, Xaba's system enables multi-robot collaboration that can increase production throughput by up to 30 times, positioning it as a transformative solution in advanced manufacturing environments (Xaba, 2025).

A3D Manufacturing

A3D Manufacturing, established in 2019, was founded to produce high-quality parts that combine scalability in production volume with cost efficiency through 3D printing technologies. Since its inception, the company has broadened its scope beyond additive manufacturing to include complementary processes such as CNC machining, injection molding, cast urethane, and a wide range of post-processing services. This diversification enables A3D to provide end-to-end solutions for modern manufacturing needs (A3DMFG, 2025).

As an industry-certified provider of professional-grade 3D printing services, A3D Manufacturing draws upon decades of accumulated expertise in additive manufacturing technologies and material science. Its service model emphasizes efficiency, precision, and collaboration, ensuring a seamless customer experience from prototyping to full-scale production. Central to the company's approach is a commitment to adaptability and stringent quality standards, guaranteeing the timely delivery of reliable, high-performance products.

A3D Manufacturing specializes in developing customized plastic and metal components that meet the requirements of companies across diverse industries and scales. Its capabilities span industrial-grade additive manufacturing, advanced finishing, and post-processing solutions. In addition, the firm demonstrates proficiency in traditional production techniques, including CNC machining, urethane casting, sheet metal cutting, and bending. Integrating advanced additive technologies with established manufacturing methods, A3D is a versatile and trusted partner in delivering innovative, sustainable, and customer-focused manufacturing solutions (Business Wire, 2023).

Geofabrica Inc.

Geofabrica, established in 2020 in Michigan, is a company dedicated to advancing and commercializing additive manufacturing technologies, with a particular focus on 3D printing systems for low-volume production of industrial components. Its portfolio encompasses a variety of services, including the fabrication of plastic, fiber-reinforced, and metal parts, as well as advanced manufacturing colocation and the design of customized production systems (Geofabrica, 2025).

The company primarily serves clients in the defense sector and private industry, offering tailored solutions designed to optimize the value of digital manufacturing investments. A notable area of expertise is expeditionary manufacturing, through which Geofabrica develops resilient systems capable of functioning effectively in demanding and resource-constrained environments. By combining technical innovation with practical adaptability, the company contributes to expanding the scope and accessibility of additive manufacturing in both strategic and commercial applications (Zoom Info, 2025).

STILRIDE

Stilride, founded in Sweden in 2020, is a technology company that applies the principles of "industrial origami" to reimagine the future of sustainable mobility. Its vision is to pioneer environmentally responsible design and manufacturing solutions by combining advanced fabrication methods with innovative materials engineering. The company's signature approach involves laser-cutting and folding a single sheet of stainless steel, much like origami, to form vehicle structures. This process significantly reduces resource consumption by achieving up to 40 percent lower weight, 70 percent fewer components, 20 percent lower material costs, and 25 percent lower labor costs than conventional production.

Stilride’s commitment to environmental responsibility is evident in its pledge to avoid using fuels harmful to the planet. Its flagship motorcycle runs on electricity and is engineered for lightweight performance and efficiency, consuming less energy than heavier vehicles. Furthermore, the company has developed flexible production units in collaboration with partners, enabling localized manufacturing. These localized production cells are designed to reduce emissions, accelerate prototyping, and substantially lower logistics costs and environmental impact.

A key enabler of this approach is toolless robotic folding, which supports local production by enhancing flexibility and cost-efficiency, even in small-batch manufacturing. By combining innovative fabrication methods with material optimization strategies that rely on a single sheet of steel, Stilride minimizes both resource consumption and production waste. Ultimately, this integrated approach not only advances sustainable design but also significantly reduces the environmental footprint of manufacturing. (Stilride, 2025).

BYD Company Ltd.

In 2024, BYD company will widely apply water-based waste solvent recycling technology in China's vehicle bases. After this recycling, the waste solvent recycling rate reaches 90%, and the amount of water-based fresh solvent is reduced by more than 60%. Also, BYD sets up two battery recycling factories, which recycled over 10.000 tons of power batteries. As for package recycling, BYD saves 324.8 tons of cardboard boxes and 295.2 tons of wooden crates. Moreover, Table 5 indicates the emission results of the BYD company.

Table 5: BYD Company Ltd. Emissions (BYD Sustainability Report, 2024)

BYD Company Ltd.	2022	2023	2024
Emission Scope 1 (t-CO2e)	550.932	931.916	1.539.251
Emission Scope 2 (t-CO2e)	7.511.038	11.409.539	8.562.574
Total GHG Emissions (t-CO2e)	8.061.970	12.341.455	10.101.826

Future Insights and Recommendations

Dark Factories Market Size and Trends

The global dark factories market size was estimated at USD 119.19 billion in 2024 and is expected to reach USD 128.43 billion in 2025. The global dark factories market is expected to grow at a compound annual growth rate of 8.7% from 2025 to 2030 to reach USD 194.60 billion by 2030. Figure 1 shows the growth trend of the market size of dark factories in billions of dollars by technology type between 2020 and 2030. Asia Pacific dark factories are expected to grow at the highest compound annual growth rate (CAGR) of over 9% from 2025 to 2030. This growth is primarily driven by advancements in automation, robotics, and artificial intelligence, which are transforming manufacturing processes. Increased demand for efficient, cost-effective, and scalable production solutions further accelerates the adoption of dark factories in the region. Key drivers of dark factory market growth include rising adoption of industrial robotics, AGVs, industrial IoT, AI, machine learning, machine vision systems, additive manufacturing, and the acceleration of digital transformation and Industry 5.0 initiatives (GVR, 2024).

The addition of machine learning (ML) and artificial intelligence (AI) to manufacturing is radically enhancing the ability of dark factories to make data-driven decisions and optimize processes independently. In the automotive, electronics, and pharmaceutical industries, the growing demand for speed and precision in manufacturing is driving the adoption of machine vision technologies and additive manufacturing processes. At the same time, the broader wave of Industry 5.0 and digital transformation initiatives is pushing the transition towards entirely automated smart factories, fueling the dark factory model's expansion.

One of the key forces behind this shift is the rising application of industrial robots, which enable production lines to run continuously with minimal human touch. The robots facilitate greater precision, speed, and reliability, allowing companies to lower operation costs and improve productivity. With the global market prioritizing scalable and flawless production, industrial robots are remaking what can be accomplished in dark factory setups.

Digitalization also plays a fundamental role in this change. Companies get immediate feedback, predictive insights, and self-directed decision-making by combining IoT, AI, and cloud computing into factory floors. Such convergence reduces downtime, optimizes efficiency, and ensures more uniformity in product quality—benefits that enhance automated manufacturing systems' competitive positions.

Here, machine vision systems become necessary. These provide advanced inspection, guidance, and identification capabilities that enable instant detection of errors and real-time quality changes. Not only is waste reduced and throughput maximized, but accuracy to rigorous product standards without human intervention.

Finally, the growing need for high-speed, high-precision production in industries propels additive manufacturing (3D printing) into takeoff. Combined with global momentum towards digitalization and automation, these forces are compelling the emergence of fully automated smart factories, with the dark factory as a key element of future industrial manufacturing.

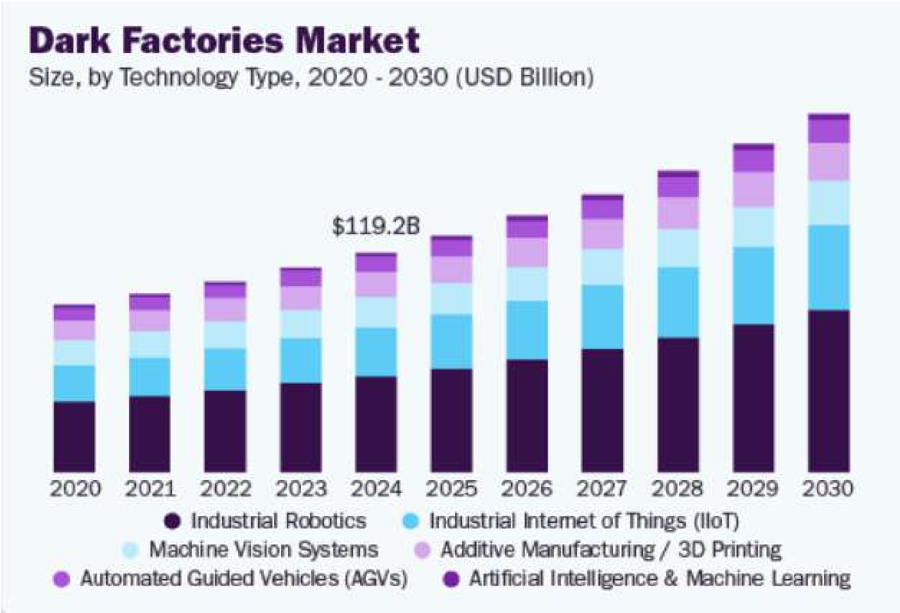

Figure 1: Dark Factories Market Size (GVR, 2024)

Technology Type Insights

In 2024, the industrial robotics segment captured the largest market revenue share with 43.8%. This share is inherently connected with the increasing design complexity, the need for shorter time-to-market cycles, and the growing need for innovation in functionality and features. As industries transition towards the total automation of production environments, applications of industrial robots have gained momentum, propelled primarily by their capacity to provide accuracy, speed, and around-the-clock operation without human oversight. Apart from simplifying productivity, the robots are essential for enhancing efficiency, eliminating operational errors, and providing continuity of quality in intense processes such as assembling, welding, and material transport. Also, the application of artificial intelligence (AI) and machine learning (ML) in robotic applications enables more sophisticated capabilities, including predictive maintenance and adaptive control, enhancing the supremacy of this segment in the dark factory scenario.

The future Industrial Internet of Things (IIoT) segment will grow at a considerable CAGR of 9.6% from 2025 to 2030. This growth is due to industrial robots' rising embeddedness in manufacturing processes, making it possible for relentless, high-speed, and precise operation with minimal human interaction. Industries such as automotive, electronics, and pharmaceuticals are shifting towards a completely automated manufacturing setup where robots enhance productivity, workplace safety, and reduce human mistakes. At the same time, innovation in robotic technologies such as collaborative robots, AI-driven automation, and adaptive robots brings more real-world deployment of dark factories. Such innovations encourage more flexibility in production lines so companies can readily maintain pace with fluctuating product demands and customer requirements. The IIoT sector is thus becoming a major enabler for the future generation of industrial automation, inspiring more growth and sophistication in dark factory systems.

End Use Industry Insights

The automotive sector held the leading position as the largest revenue contributor to the market in 2024, driven primarily by large investments in industrial robots to improve accuracy, speed, and overall process efficiency. In the sector, manufacturers use robot systems more intensively to manage repetitive and large-volume tasks, saving labor costs and human error and enhancing production reliability. By enabling around-the-clock production, real-time scalability, and replicable outputs, robotics has become central to the industry's competitiveness. Moreover, the automotive industry's high financial capabilities and strategic affinity toward automation have positioned it as a leader in the dark factory trend, and it continues to lead by driving segmental expansion. Figure 2 represents the share of these sectors in the dark factory trend.

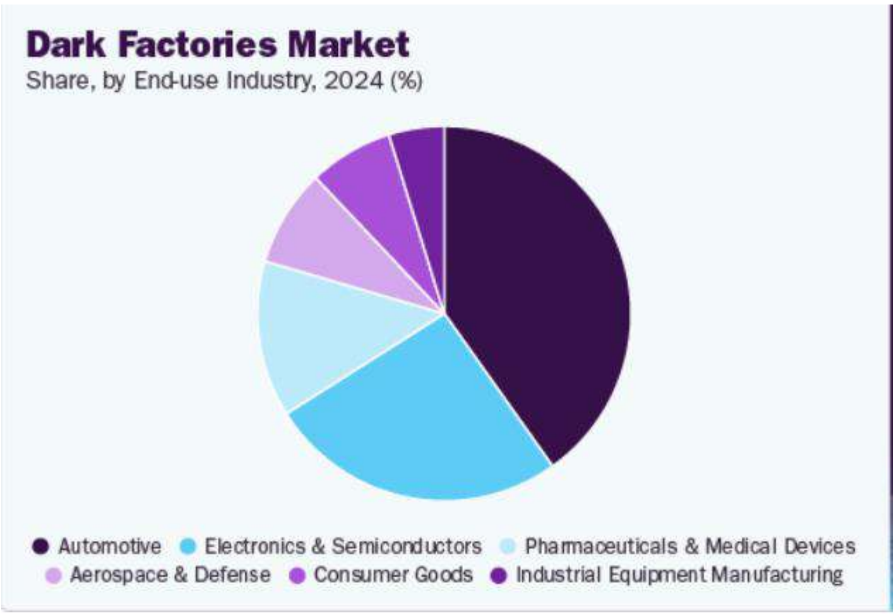

Figure 2: Dark Factories Market Share by End-use Industry (GVR, 2024)

The pharmaceuticals and medical devices segment is expected to grow at the highest CAGR of 2025-2030. Industrial robotics is being adopted rapidly by companies in the industry for automating repetitive and sensitive tasks because of increasing requirements for precision, sterility, and efficiency in manufacturing. Robotic solutions ensure consistent high-speed production, reduce the chance of contamination, and also assure compliance with stringent regulatory standards. The growing need to mechanize operations without losing product quality fuels investment in robotics. Additionally, advancements in robotic flexibility and integration enable pharmaceutical manufacturers to respond to product changes and manufacture them in different capacities without difficulties, leading to the growth of this industry at a very rapid rate.

Regional Insights

The global dark factories market is entering a period of rapid expansion, with distinct regional dynamics shaping its trajectory. In the United States, growth is projected to accelerate between 2025 and 2030, supported by strong technological innovation, reshoring strategies to strengthen supply chain resilience, and government investment in smart manufacturing and automation R&D (GVR, 2024).

Europe currently leads the market, accounting for 50% of global revenue 2024. This dominance is underpinned by the region’s advanced manufacturing base, rising labor shortages, and high operating costs, collectively driving automation adoption. National Industry 5.0 policies and incentives for energy-efficient production further reinforce Europe’s leadership. Within the region, the United Kingdom and Germany illustrate different growth drivers: the UK emphasizes automation to counter labor shortages and meet regulatory and sustainability standards, while Germany's precision engineering industries, coupled with its commitment to energy efficiency, are accelerating the integration of dark factory models (GVR, 2024).

Asia-Pacific is expected to record the fastest growth through 2030, reflecting the region's rapid advancements in automation, robotics, and artificial intelligence. Japan is experiencing strong adoption in industries such as automotive and electronics, where dark factories reduce labor costs, increase capacity, and improve efficiency. Meanwhile, China is emerging as a key global hub, leveraging large-scale investments in robotics and AI to boost productivity and sustainability, reshaping the global manufacturing landscape (GVR, 2024).

The market for dark factories is expanding worldwide, driven by technological innovation, labor market pressures, sustainability imperatives, and supportive industrial policies. These factors collectively position dark factories as a transformative model for the future of global manufacturing.

CONCLUSION

The global dark factories market analysis highlights its role as a transformative model for the future of manufacturing. Rapid advancements in automation, robotics, artificial intelligence, and the Industrial Internet of Things (IIoT) enable production systems with unprecedented speed, precision, and resilience. By minimizing human intervention, dark factories address labor shortages, reduce operational errors, and enhance efficiency across automotive, electronics, and pharmaceutical industries. At the same time, the integration of machine vision, additive manufacturing, and AI-driven predictive systems reinforces their ability to maintain high-quality standards while supporting continuous, cost-effective production. These technological cooperations accelerate digital transformation and position dark factories as a critical driver of competitiveness in global markets.

Regional dynamics further illustrate the diversity of adoption pathways. Europe currently leads in market share due to its established industrial base and supportive Industry 5.0 policies, while North America emphasizes innovation and reshoring strategies to strengthen supply chain resilience. Asia-Pacific, however, is expected to experience the fastest growth, reflecting significant investments in robotics, AI, and sustainable production methods, particularly in Japan and China. Collectively, these trends underscore the dark factory's capacity to reshape industrial practices by aligning efficiency, sustainability, and resilience. Looking forward, the continued expansion of dark factories will depend not only on technological progress but also on policies that balance economic efficiency with environmental stewardship and workforce adaptation, ensuring that the future of manufacturing remains both innovative and inclusive.

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