Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250358
Published: June 17, 2025

Modeling Technological Enablers for Blockchain in Automotive Supply Chains: A Multi-Method Approach

Avinash Chauhan
PhD Student, Operations and Supply Chain
Vinod Gupta School of Management, Indian Institute of Technology Kharagpur
avinashchauhan15@gmail.com

M Vimala Rani
Assistant Professor, Operations management & Decision Sciences
IIM Tiruchirappalli
vimalarani@iimtrichy.ac.in

Abstract

The automotive supply chain is undergoing a profound digital transformation, with blockchain technology emerging as a promising solution to address critical challenges related to traceability, security, and interoperability. Despite its potential, the practical adoption of blockchain in this sector remains limited, often hindered by fragmented technological readiness and a lack of structured understanding of key enablers. This study aims to identify, validate, and structure the technological enablers that facilitate blockchain implementation in the automotive domain.Drawing from a systematic literature review and expert input, an initial set of 30 enablers was screened using the Fuzzy Delphi Method (FDM) to establish consensus on their relevance. A total of 12 enablers were accepted and subsequently analyzed using Interpretive Structural Modeling (ISM) to uncover their contextual interrelationships and hierarchical influence. To further categorize these enablers, MICMAC analysis was applied, mapping them into driver, linkage, and dependent categories based on their driving and dependence power.The findings reveal a multi-level structure of technological readiness, where core infrastructure elements—such as system integration, platform scalability, and technical standards—serve as foundational drivers, while trust-related and performance-focused enablers emerge as dependent outcomes. The study offers a strategic roadmap for blockchain deployment, emphasizing the prioritization of high-leverage enablers in early implementation stages.By integrating FDM, ISM, and MICMAC, this research advances both theoretical understanding and managerial practice, providing a robust framework for blockchain adoption in complex industrial ecosystems. The study concludes with recommendations for future research, including the incorporation of organizational and environmental dimensions.

Keywords
Blockchain Adoption, Automotive Supply Chain, Digital Transformation, Fuzzy Delphi Method, Interpretive Structural Modeling (ISM), and Industry 4.0.

1. Introduction
The automotive supply chain is facing unprecedented transformation driven by technological disruption, regulatory shifts, and rising consumer expectations for sustainability and transparency. As production networks become increasingly complex and globally distributed, ensuring real-time visibility, trust, and secure data exchange among multiple stakeholders has become a pressing challenge (Kamble et al. 2019; Wamba & Queiroz 2022). In this context, **blockchain technology** is widely regarded as a promising enabler for enhancing supply chain coordination, product traceability, and transactional security in the automotive domain (Fraga-Lamas and Fernández-Caramés, 2020; Kusi-

Sarpong et al.2022).

Blockchain's core attributes—immutability, decentralization, transparency, and automation through smart contracts—hold significant potential to improve information reliability, eliminate fraud, and streamline cross-organizational workflows (Saberi et al. 2019; Kshetri 2018). Automotive leaders such as BMW, Ford, and Renault have initiated blockchain pilots for part authentication, battery traceability, and warranty management. However, despite such developments, **widespread adoption remains limited**, particularly due to a lack of technological readiness, interoperability with legacy systems, and insufficient standardization (Chauhan and Rani 2025; Min, 2019; Karakış et al. 2021).

While prior studies have acknowledged various drivers and barriers to blockchain adoption in manufacturing and logistics, few have provided a **structured understanding of the interrelationships among technological enablers**, especially within the automotive supply chain. Most research is either conceptual or based on isolated factor analyses, lacking a hierarchical or systemic view of how technical factors interact to facilitate adoption (Queiroz and Wamba 2019; Kamble et al. 2020).

To address this gap, the present study focuses on the **technological dimension** of blockchain adoption in the automotive sector. It argues that a thorough understanding of technological enablers—and their contextual relationships—is critical for designing scalable, secure, and integrated blockchain solutions. This is particularly relevant for automotive firms operating in a dual landscape of traditional and electric vehicle supply chains, where technological transformation must align with existing infrastructures and evolving digital architectures.

Accordingly, the study sets out to identify and structure the technological enablers that support blockchain adoption in automotive supply chains. Using a **three-phase hybrid methodology**, it first screens and validates enablers using the **Fuzzy Delphi Method (FDM)**, then applies **Interpretive Structural Modeling (ISM)** to understand the hierarchy of influence, and finally uses **MICMAC analysis** to classify enablers based on their driving and dependence power.
The study is guided by the following **research questions**:

RQ1: What are the critical technological enablers for blockchain adoption in the automotive supply chain, as validated through expert consensus?
RQ2: How are these enablers interrelated, and what is their hierarchical structure based on contextual influence?
RQ3: Which enablers act as strategic drivers, and which are dependent outcomes in the blockchain adoption process?

Through this approach, the study makes the following key contributions:
1. It synthesizes and validates a comprehensive set of blockchain-related technological enablers specific to the automotive sector.
2. It provides a multi-level structural hierarchy that helps identify foundational enablers and dependent outcomes.
3. It offers a strategic framework for practitioners to prioritize investments and roadmap blockchain deployment initiatives based on systemic interdependencies.

4.The findings of this study contribute to both academic theory and industrial practice. Academically, the research advances the digital supply chain literature by offering a hierarchical and interdependent view of technological enablers tailored to the automotive sector. Practically, it provides supply chain managers, IT architects, and technology strategists with a validated and prioritized roadmap for blockchain implementation, thus enabling more informed and resource-efficient decisions.

2. Literature Review

2.1 Blockchain Applications in Supply Chains

Blockchain technology has garnered significant attention in supply chain management (SCM) due to its potential to enhance transparency, traceability, and security across complex networks. As a decentralized ledger system, blockchain ensures immutable recording of transactions, which is particularly beneficial in intricate supply chains where trust and verification are paramount. Saberi et al. (2019) highlight blockchain's role in improving traceability and provenance, addressing issues like counterfeiting and supplier management. Furthermore, Wang et al. (2020)

emphasize that blockchain facilitates real-time data sharing among stakeholders, leading to more efficient and responsive supply chain operations. The integration of blockchain with other emerging technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), further amplifies its impact on SCM. For instance, Kamble et al. (2019) discuss how the convergence of blockchain with Industry 4.0 technologies can lead to more sustainable and lean manufacturing practices. Additionally, Francisco and Swanson (2018) argue that blockchain's ability to provide a transparent and tamper-proof ledger can significantly enhance supply chain transparency, thereby fostering greater trust among stakeholders.

2.2 Blockchain in the Automotive Supply Chain

The automotive industry, characterized by intricate networks of suppliers and manufacturers, stands to gain significantly from blockchain integration. Blockchain can enhance supply chain transparency, enabling stakeholders to monitor and verify the movement of parts and vehicles. This capability is crucial for addressing challenges such as counterfeit parts, unauthorized modifications, and ensuring the ethical sourcing of materials. Wissuwa and Durach (2023) emphasize that blockchain's ability to provide real-time access to information can streamline operations, reduce delays, and improve inventory control.

Moreover, the implementation of smart contracts within blockchain platforms can automate various processes in the automotive supply chain. Bai and Sarkis (2020) discuss how smart contracts can facilitate automatic execution of agreements once predefined conditions are met, thereby reducing the potential for human error and enhancing operational efficiency. This automation is particularly beneficial in managing complex warranty claims, recall processes, and compliance with regulatory standards.

2.3 Technological Enablers of Blockchain Adoption

The successful adoption of blockchain in the automotive supply chain hinges on several technological enablers:
Firstly, **system integration** is vital. Seamless integration with existing legacy systems ensures that blockchain solutions can coexist with current infrastructure, avoiding disruptions. Zheng et al. (2020) highlight the importance of developing interoperable systems that can facilitate smooth data exchange between blockchain platforms and traditional enterprise systems.

Secondly, **scalability and performance** are critical considerations. As supply chains involve vast amounts of data and numerous transactions, blockchain platforms must be scalable and capable of handling high throughput without compromising performance. Yoo and Won (2018) discuss the challenges associated with scaling blockchain solutions and the need for optimizing consensus mechanisms to enhance performance.

Thirdly, **data security and privacy** are paramount. Ensuring the confidentiality and integrity of sensitive information is essential, especially in the automotive sector where proprietary data is frequently exchanged. Casino et al. (2019) explore the cryptographic features of blockchain that provide a foundation for secure data sharing among authorized parties, while also addressing concerns related to data privacy.

Fourthly, **standardization and interoperability** are necessary for widespread blockchain adoption. The development of industry-wide standards and protocols is essential for facilitating interoperability between different blockchain systems and stakeholders. Zheng et al. (2020) emphasize the need for standardized frameworks to ensure that disparate blockchain solutions can effectively communicate and share data.

Lastly, the use of **smart contracts** can significantly enhance efficiency. Automating processes through smart contracts reduces the potential for human error and ensures that predefined conditions are met before transactions are completed. Christidis and Devetsikiotis (2016) discuss the role of smart contracts in automating complex processes, thereby improving operational efficiency and reducing transaction costs.

2.4 Gaps and Research Motivation

While the literature acknowledges the potential of blockchain in enhancing automotive supply chains, several gaps persist:

One notable gap is the lack of exploration into the **contextual relationships** among technological enablers. Many studies identify individual enablers but fail to explore the interdependencies and hierarchical relationships among them.

Understanding how these factors influence each other is crucial for strategic implementation. Dasaklis et al. (2022) suggest that a more nuanced analysis of these interrelationships can provide deeper insights into effective blockchain adoption strategies.

Another gap is the scarcity of **sector-specific analysis**. There is a lack of focused research on the automotive sector's unique challenges and requirements concerning blockchain adoption. Given the industry's complexity, tailored studies are necessary to address specific needs. Wissuwa and Durach (2023) highlight the importance of sector-specific research to understand the distinct dynamics and requirements of the automotive supply chain.

Furthermore, there is a need for **empirical validation**. Much of the existing research is conceptual, lacking empirical data to support proposed frameworks and models. Real-world case studies and pilot projects can provide valuable insights into practical applications and outcomes. Wang et al. (2020) emphasize the importance of empirical studies to validate theoretical models and understand the practical implications of blockchain adoption in supply chains.Addressing these gaps, this study aims to identify and model the critical technological enablers of blockchain adoption in the automotive supply chain. By employing methodologies such as the Fuzzy Delphi Method and Interpretive Structural Modeling (ISM), the research seeks to provide a structured framework that elucidates the relationships among enablers, offering actionable insights for practitioners and policymakers.

3. Methods

The To identify, validate, and model the critical technological enablers driving blockchain adoption in the automotive supply chain, a two-stage methodological approach was implemented. This study first applied the **Fuzzy Delphi Method (FDM)** to shortlist enablers based on expert consensus and subsequently utilized **Interpretive Structural Modeling (ISM)** to map the contextual relationships among them.

3.1 Identification of Preliminary Enablers

A comprehensive literature review was undertaken to extract an initial set of 30 technological enablers influencing blockchain adoption in the supply chain context. Sources included high-impact journals, industry reports, and recent reviews (Saberi et al., 2019; Wang et al.2020; Zheng et al. 2020). These enablers were compiled and presented to a panel of domain experts for validation and screening.

3.2 Expert Panel Composition

The criteria for expert selection were designed to ensure the inclusion of participants with extensive and relevant expertise in digital supply chains, blockchain implementation, and the automotive sector. The selection process followed purposive sampling, aimed at capturing a broad and informed perspective. The inclusion requirements were:

i. **A minimum of fifteen years of professional experience** in the automotive industry or related digital supply chain domains, including positions in OEMs, tier-1 suppliers, and technology consulting firms.
ii. **Availability and willingness to participate actively** in the research process, including engagement in the Fuzzy Delphi and ISM-based assessments.
iii. **Independence from potential conflicts of interest**, ensuring that none of the participants had prior involvement in related research studies or commercial interests that could bias their input.
iv. **Strong familiarity with blockchain and supply chain digitalization**, along with effective communication skills in English, which was the medium of instruction and data collection.
v. **Institutional representation across leading automotive manufacturers and technology solution providers** operating in the Indian and global automotive supply chain ecosystem.
These criteria helped in forming a credible expert panel comprising eight senior professionals whose designations ranged from senior managers and program heads to directors and consultants across globally reputed firms. This diverse yet specialized pool ensured a robust evaluation of the technological enablers of blockchain adoption.

Table 1. Expert Panel Composition

Expert ID	Affiliation	Designation	Domain Expertise	Experience (Years)
E1	Tata Motors	Senior Manager – SCM	Blockchain, IoT, Supply Chain	16

E2	Mahindra & Mahindra	General Manager – IT	ERP, Blockchain Integration	18
E3	Hyundai Motor India	Senior Technical Consultant	Connected Vehicles, Industry 4.0	15
E4	Škoda Auto Volkswagen India	Head – Logistics Operations	Global SCM, Digital Transformation	21
E5	BYD Auto	Director – Digital Projects	Smart Manufacturing, Blockchain	14
E6	Tata Consultancy Services	Principal Consultant	Blockchain Strategy, Architecture	20
E7	Bosch Global Software	Product Head – Automotive	Automotive Software, Traceability	17
E8	Ford India	Senior Program Manager	Digital Supply Chain, Systems Design	19

This expert panel provided responses using a structured FDM questionnaire, assessing the degree of influence each enabler has on blockchain adoption.

3.3 Fuzzy Delphi Method (FDM)

The Fuzzy Delphi Method was used to quantify expert consensus on the relevance of each of the 30 enablers. Experts rated each enabler's influence on a five-point linguistic scale: No influence, Very Low, Low, High, and Very High. These responses were transformed into **triangular fuzzy numbers** based on the conversion scale defined by Chen and Hwang (1992), as detailed in Table 2.

Table 2. Triangular Fuzzy Scale for Expert Judgment
(Adapted from Chen & Hwang, 1992)

Linguistic Response	**Linguistic Scale**	**Fuzzy Members**
No influence (N)	0	(0.00, 0.00, 0.25)
Very low influence (VL)	1	(0.00, 0.25, 0.50)
Low influence (L)	2	(0.25, 0.50, 0.75)
High influence (H)	3	(0.50, 0.75, 1.00)
Very high influence (VH)	4	(0.75, 1.00, 1.00)

The fuzzy ratings provided by each expert were aggregated, and the centroid method was used for defuzzification. The average of all defuzzified values served as the threshold; enablers scoring above this threshold were selected for structural modeling.

3.4 Interpretive Structural Modeling (ISM) and MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) Analysis

The Following the screening of technological enablers using the Fuzzy Delphi Method, the validated set of enablers was analyzed using **Interpretive Structural Modeling (ISM)** to explore and structure their contextual interrelationships. ISM is a well-established methodology for converting complex qualitative assessments into an interpretable multilevel hierarchical model (Warfield, 1974). Experts were asked to assess the presence and direction of contextual relationships between enabler pairs through a structured pairwise comparison. These binary judgments were compiled into a **Structural**

Self-Interaction Matrix (SSIM), which was subsequently converted into an initial **reachability matrix** by applying standard transitivity rules.

An iterative level partitioning process was performed on the reachability matrix to derive a hierarchy of enablers, distinguishing those that act as foundational drivers from those that are more dependent or outcome-oriented. The

resulting ISM-based digraph illustrated the flow of influence among enablers and served as a strategic map for prioritizing blockchain implementation efforts in the automotive supply chain.
To further enhance the interpretive insight provided by the ISM model, a **MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement)** analysis was conducted. MICMAC uses the final reachability matrix to calculate the **driving power** (the total number of variables an enabler influences) and **dependence power** (the total number of variables that influence it) for each enabler. Based on these two metrics, enablers were classified into four categories:

- **Autonomous Enablers**, with weak driving and dependence power, are relatively disconnected from the system.
- **Dependent Enablers**, with low driving but high dependence, represent the outcomes of system behavior.
- **Linkage Enablers** exhibit both high driving and high dependence power, indicating a high degree of mutual influence. These enablers are unstable and require close managerial attention.
- **Driving Enablers**, with strong driving but weak dependence power, form the foundation of the system and should be prioritized for strategic interventions.

The combined ISM–MICMAC approach offers a holistic framework: ISM uncovers the hierarchical structure and influence pathways, while MICMAC quantitatively categorizes enablers based on systemic influence. Together, they provide both conceptual depth and actionable guidance for managers and policymakers pursuing blockchain-based transformation in the automotive supply chain.

4. Results

4.1. Screening of Technological Enablers Using Fuzzy Delphi Method

To determine the most relevant technological enablers for blockchain adoption in the automotive industry, the Fuzzy Delphi Method was applied using expert input from eight professionals with academic and industrial expertise in digital supply chains. Each of the 30 initially shortlisted enablers was rated using a five-point linguistic scale and converted into triangular fuzzy numbers to account for uncertainty and imprecision in expert judgment. The central values of these fuzzy scores were aggregated using the geometric mean to realistically reflect expert consensus. Final defuzzified values were obtained and compared against a decision threshold of 0.6, with enablers scoring above this value being retained for further analysis.

Table 3. Fuzzy Delphi Results for Technological Enablers of Blockchain Adoption in the Automotive Sector

S. No.	Technological Enabler	Fuzzy p	Fuzzy q	Fuzzy r	Defuzzified Mean	Decision	Dimension
1	Scalability of Blockchain Platforms	0.5	0.7041	0.9	0.701367	Accept	Core Functionality & Infrastructure
2	Latency and Transaction Speed	0.1	0.3097	0.5	0.3032	Reject	Performance & Reliability
3	Consensus Mechanism Efficiency	0.5	0.6733	0.9	0.6911	Accept	Core Functionality & Infrastructure
4	System Integration with Legacy Infrastructure	0.5	0.6595	0.9	0.6865	Accept	Core Functionality & Infrastructure
5	Cloud and Edge Compatibility	0.1	0.2962	0.5	0.2987	Reject	Core Functionality & Infrastructure
6	Blockchain-as-a-Service (BaaS)	0.1	0.3141	0.5	0.3047	Reject	Core Functionality & Infrastructure
7	On-chain and Off-chain Data Storage	0.1	0.2938	0.5	0.2979	Reject	Core Functionality & Infrastructure
8	Data Immutability and Integrity	0.5	0.6903	0.9	0.6968	Accept	Security, Privacy & Trust
9	Real-time Data Processing Capabilities	0.5	0.717	0.9	0.7057	Accept	Performance & Reliability
10	Secure Data Sharing Across Stakeholders	0.1	0.3154	0.5	0.3051	Reject	Security, Privacy & Trust
11	Decentralized Access Control Mechanisms	0.1	0.3175	0.5	0.3058	Reject	Security, Privacy & Trust
12	Auditability and Traceability of Transactions	0.5	0.709	0.9	0.703	Accept	Security, Privacy & Trust

13	Smart Contract Reliability and Execution Accuracy	0.5	0.7065	0.9	0.7022	**Accept**	Core Functionality & Infrastructure
14	Protection Against Data Tampering	0.5	0.6978	0.9	0.6993	**Accept**	Security, Privacy & Trust
15	Robustness to Cyber Threats and Hacks	0.1	0.3052	0.5	0.3017	**Reject**	Security, Privacy & Trust
16	User Identity Verification and Authentication	0.7	0.8158	0.9	0.8053	**Accept**	Security, Privacy & Trust
17	Encryption Standards and Protocols	0.1	0.3197	0.5	0.3066	**Reject**	Security, Privacy & Trust
18	Privacy-preserving Computation (ZKPs)	0.1	0.2918	0.5	0.2973	**Reject**	Security, Privacy & Trust
19	Integration with IoT Devices and Sensors	0.5	0.6786	0.9	0.6929	**Accept**	Interoperability & Integration
20	API Support for Interoperability Across Platforms	0.1	0.3073	0.5	0.3024	**Reject**	Interoperability & Integration
21	Compatibility with ERP/SCM Systems	0.5	0.6782	0.9	0.6927	**Accept**	Interoperability & Integration
22	Cross-Blockchain Communication Capability	0.1	0.303	0.5	0.301	**Reject**	Interoperability & Integration
23	Platform Stability and Uptime	0.1	0.3131	0.5	0.3044	**Reject**	Performance & Reliability
24	Ease of System Upgrades and Versioning	0.1	0.2935	0.5	0.2978	**Reject**	Performance & Reliability
25	Fault Tolerance and Error Recovery	0.1	0.3191	0.5	0.3064	**Reject**	Performance & Reliability
26	Monitoring and Diagnostic Tools Availability	0.1	0.2927	0.5	0.2976	**Reject**	Performance & Reliability
27	Blockchain Maturity for Automotive Use Cases	0.1	0.2982	0.5	0.2994	**Reject**	Technological Readiness & Applicability
28	Availability of Developer Toolkits and SDKs	0.1	0.3109	0.5	0.3036	**Reject**	Interoperability & Integration
29	Tokenization and Asset Representation	0.1	0.2919	0.5	0.2973	**Reject**	Core Functionality & Infrastructure
30	Availability of Technical Standards and Protocols	0.5	0.6818	0.9	0.6939	**Accept**	Core Functionality & Infrastructure

Out of the thirty technological enablers evaluated in this study, twelve were ultimately accepted based on expert consensus, as summarized in Table 3. These enablers represent the most critical and practically viable factors influencing blockchain implementation in the automotive sector. Among them, *User Identity Verification and Authentication* received the highest rating across all expert responses, consistently identified as “extremely important.” This finding underscores the growing emphasis on secure identity management, robust access control, and data protection in decentralized ecosystems, especially where sensitive stakeholder interactions occur frequently.
Other highly rated enablers—such as *System Integration with Legacy Infrastructure*, *Scalability of Blockchain Platforms*, and

Auditability and Traceability of Transactions—highlight the foundational need for interoperability, processing capability, and operational transparency. These features are particularly relevant in the automotive domain, where complex supply chain networks and fragmented information systems often hinder effective coordination. Their acceptance indicates that for blockchain to be realistically deployed, it must be compatible with existing enterprise architectures and capable of enhancing visibility and accountability across tiers.
In addition, enablers like *Smart Contract Reliability and Execution Accuracy*, *Real-time Data Processing Capabilities*, and

Data Immutability and Integrity reflect an increasing demand for automation, responsiveness, and trust in digital transaction records. These technical features are central to eliminating manual inefficiencies, reducing errors, and enabling real-time decision-making in supply chain operations. Moreover, the inclusion of *Compatibility with ERP/SCM Systems*, *Integration with IoT Devices and Sensors*, and *Availability of Technical Standards and Protocols* suggests a clear preference for solutions that can seamlessly integrate with existing digital infrastructures while maintaining scalability and adherence to common industry norms(Chauhan and Rani 2024b).

To better understand the strategic orientation of these enablers, each was classified into one of four key technological dimensions: *Core Functionality and Infrastructure*, *Security, Privacy, and Trust*, *Interoperability and Integration*, and *Performance and Reliability*. Interestingly, the majority of accepted enablers fell under *Core Functionality and Infrastructure* (five enablers), followed by *Security, Privacy, and Trust* (four enablers). This distribution suggests a dual priority—building a robust, scalable blockchain foundation while ensuring high levels of data integrity and protection. The relatively smaller number of accepted enablers under *Interoperability and Integration* (two enablers) and *Performance and Reliability* (one enabler) reflects a more focused prioritization by experts, favoring those elements that directly contribute to trustworthiness and operational readiness over generalized performance enhancements.

Rather than presenting the accepted enablers in a separate figure, their importance has been articulated through the discussion above, which connects each enabler with its practical implications in the automotive supply chain. This approach not only avoids redundancy but also ensures that the enablers are interpreted within a context that aligns with the sector's current digital transformation needs.

With the acceptance of these twelve enablers, the next phase of the study involves applying Interpretive Structural Modeling (ISM). This methodology will allow for a deeper examination of the relationships among the enablers, particularly their driving and dependence powers. Ultimately, the ISM analysis will generate a hierarchical framework that supports informed decision-making for blockchain implementation strategies in the automotive domain.

4.2. Interpretive Structural Modeling and MICMAC Analysis

The Following the Fuzzy Delphi evaluation, Interpretive Structural Modeling (ISM) was employed to explore the contextual relationships among the 12 accepted technological enablers. ISM helps structure complex systems by identifying how variables influence one another and organizing them into a multi-level hierarchy. This method enables the transformation of vague and poorly articulated models into a well-defined framework for decision-making.

The process began with the development of the Structural Self-Interaction Matrix (SSIM), where pairwise relationships among enablers were established based on expert input. These relationships were then converted into a binary Reachability Matrix, which was refined to account for transitivity. Level partitioning was conducted to classify each enabler into distinct layers based on their reachability and antecedent sets.

The resulting hierarchical model is presented in **Figure 1**. At the base of the hierarchy (**Level 4**), enablers such as *Scalability of Blockchain Platforms*, *Availability of Technical Standards and Protocols*, and *System Integration with Legacy Infrastructure* act as foundational drivers. These enablers have strong independent influence and are critical for enabling the rest of the blockchain ecosystem in the automotive context.

Moving upward, **Level 3** contains enablers that integrate blockchain with existing systems and technologies: *User Identity Verification and Authentication*, *Integration with IoT Devices and Sensors*, and *Compatibility with ERP/SCM Systems*. These enablers are crucial for ensuring seamless data exchange and secure interoperability across platforms.

In **Level 2**, enablers such as *Smart Contract Reliability and Execution Accuracy*, *Real-time Data Processing Capabilities*, and *Data Immutability and Integrity* contribute directly to operational effectiveness. They depend on the successful implementation of the infrastructure-level and integration-focused enablers.

Finally, **Level 1** features the most outcome-driven enablers: *Consensus Mechanism Efficiency*, *Auditability and Traceability of Transactions*, and *Protection Against Data Tampering*. These enablers exhibit high dependence on other factors and represent the end results of a successful blockchain implementation.

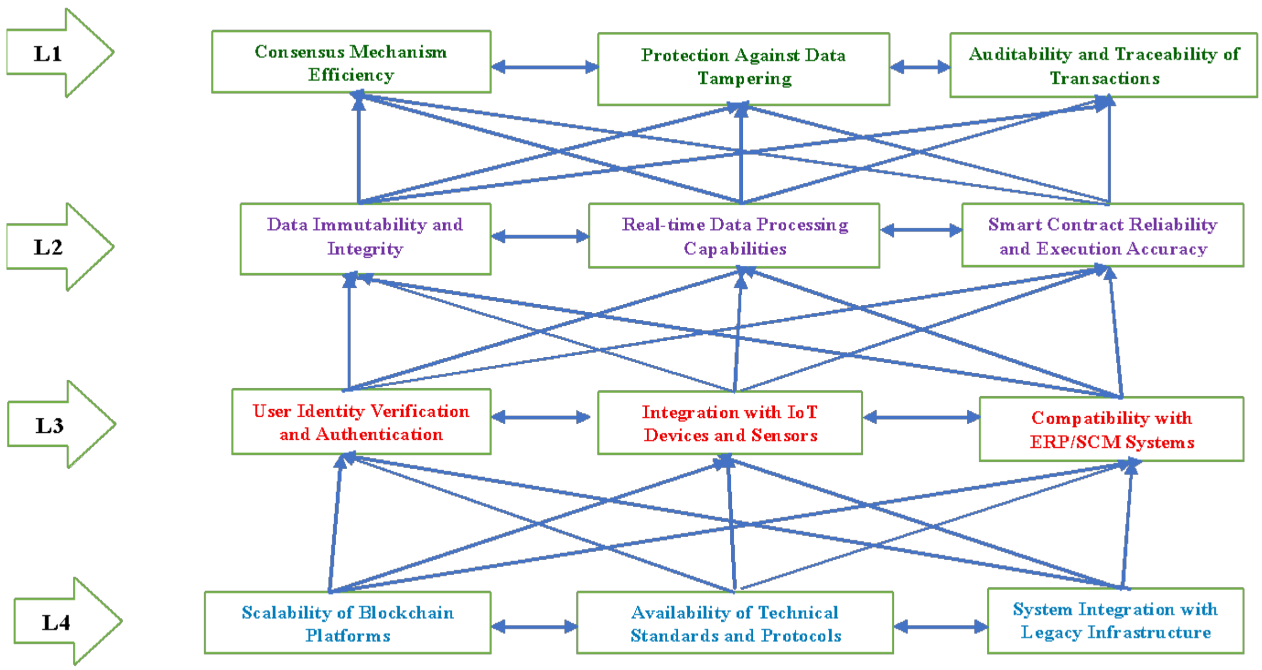

Figure 1. Interpretive Structural Modeling (ISM) Hierarchy of Technological Enablers

To further validate the ISM findings and understand the classification of enablers based on their influence and dependency, a MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) analysis was conducted. MICMAC categorizes variables into four clusters: autonomous, dependent, linkage, and driver.

As shown in **Figure 2**, the majority of the accepted enablers fall into three main clusters. The enablers in the **driver quadrant**—*Scalability of Blockchain Platforms*, *Availability of Technical Standards and Protocols*, and *System Integration with Legacy Infrastructure*—have high driving power but low dependence. These are the most strategic levers in the system.

Enablers such as *User Identity Verification and Authentication*, *Integration with IoT Devices and Sensors*, and *Compatibility with ERP/SCM Systems* are classified as **linkage variables**, which possess both high driving and dependence power. These enablers are dynamic in nature and require careful attention due to their potential to influence and be influenced by multiple others.

The **dependent quadrant** includes enablers like *Real-time Data Processing Capabilities*, *Smart Contract Reliability and Execution Accuracy*, *Consensus Mechanism Efficiency*, *Auditability and Traceability of Transactions*, and *Protection Against Data Tampering*. These enablers are more likely to be outcomes of systemic improvements, rather than primary levers of change.

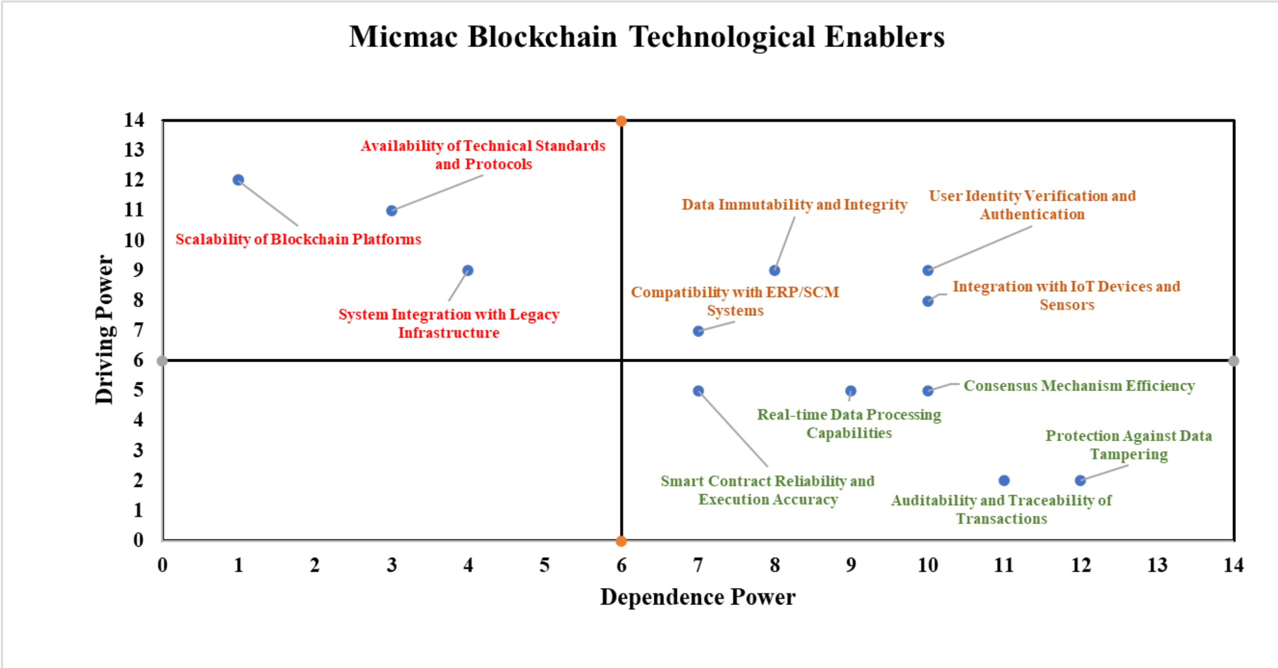

Figure 2. MICMAC Analysis of Technological Enablers for Blockchain Adoption

The combination of ISM and MICMAC analyses offers a comprehensive view of the technological landscape for blockchain implementation. While ISM establishes a hierarchical structure, MICMAC confirms the strategic importance of specific enablers by identifying their role as drivers, linkages, or dependents. Together, these methods offer clear guidance for prioritizing implementation efforts in blockchain-based digital transformation across automotive supply chains.

.

5. Theoretical and Managerial Implications

This study contributes to both theory and practice by identifying and structuring the most critical technological enablers for blockchain adoption in the automotive supply chain context. The integrated use of the Fuzzy Delphi Method, Interpretive Structural Modeling (ISM), and MICMAC analysis has yielded a robust framework that advances academic understanding and offers actionable insights for practitioners.

5.1 Theoretical Implications

From a theoretical standpoint, this research extends the literature on digital transformation and blockchain integration by systematically identifying, validating, and structuring enablers through a multi-method approach. First, the Fuzzy Delphi method provides a structured way to address uncertainty in expert-driven prioritization of enablers, overcoming the limitations of conventional consensus techniques. The resulting set of 12 validated enablers addresses a knowledge gap in current literature, which often focuses on isolated success factors without offering a structured view of interdependencies.

The ISM-based hierarchy offers a theoretical model that categorizes enablers across four levels—ranging from foundational infrastructure to operational outcomes. This layered structure contributes to the theoretical discourse on socio-technical systems and change management in Industry 4.0 environments by articulating how core technological components interact to drive successful blockchain deployment. In particular, the placement of *Scalability of Blockchain Platforms*, *System Integration with Legacy Infrastructure*, and *Availability of Technical Standards and Protocols* at the highest structural level (Level 4) supports the theoretical understanding that digital transformation must begin with the resolution of infrastructural and interoperability challenges.

Further, the MICMAC analysis confirms and enriches the ISM model by classifying enablers into drivers, linkages, and dependents based on their influence and dependence power. This dual perspective strengthens existing models in technology adoption literature by accounting not just for factor significance, but also for system behavior dynamics. It highlights that certain enablers, such as *User Identity Verification and Authentication* and *ERP/SCM Compatibility*, occupy unstable positions with both high driving and dependence power—underscoring their role in feedback-intensive system evolution.

Collectively, this research contributes a comprehensive, empirically validated structure of technological enablers that scholars can further refine, extend to other sectors, or integrate with organizational and environmental perspectives within frameworks like the TOE (Technology-Organization-Environment) or TAM (Technology Acceptance Model).

5.2 Managerial Implications

For practitioners and decision-makers in the automotive industry, this study offers clear, prioritized guidance on how to approach blockchain implementation in a strategic, stepwise manner.

Managers should begin by focusing on the enablers identified at the foundational level of the ISM hierarchy. These include *System Integration with Legacy Infrastructure*, *Scalability of Blockchain Platforms*, and *Availability of Technical Standards and Protocols*. These elements are indispensable for ensuring that blockchain solutions can function within existing IT environments, accommodate growing transaction volumes, and align with industry-wide interoperability protocols. Investments in these areas should be prioritized early in the implementation roadmap.

The enablers in the intermediate levels—such as *User Identity Verification*, *Integration with IoT Devices*, and *ERP/SCM Compatibility*—require simultaneous attention. These serve as bridges between core infrastructure and operational capabilities (Chauhan and Rani 2024a). For instance, secure identity management is not only a technical requirement but also a critical trust-building mechanism in decentralized systems.

Operational-level enablers like *Smart Contract Reliability*, *Real-time Data Processing*, and *Data Immutability* should be treated as performance targets that depend on upstream technological readiness. These enablers directly affect transactional accuracy, process automation, and supply chain responsiveness—outcomes that are visible to stakeholders and often form the basis for measuring the success of digital initiatives.

Finally, the MICMAC analysis underscores the strategic importance of addressing the high-driving power enablers early, as improvements in these areas can catalyze positive ripple effects throughout the blockchain system. Linkage enablers, while influential, require careful management due to their dual sensitivity to upstream and downstream changes. Dependent enablers like *Consensus Mechanism Efficiency* and *Auditability* serve as performance indicators and should be closely monitored to evaluate the effectiveness of broader blockchain strategies.

In practice, this structured understanding can support capability audits, investment prioritization, and change management planning for firms seeking to deploy blockchain technology at scale.

6. Conclusion and Future Direction

This study systematically identified, evaluated, and structured the key technological enablers for blockchain adoption in the automotive supply chain sector. Using a hybrid methodology that integrated the Fuzzy Delphi Method, Interpretive Structural Modeling (ISM), and MICMAC analysis, the research addressed the complex interdependencies among technological factors and provided a strategic roadmap for effective blockchain implementation.

The initial screening through the Fuzzy Delphi Method led to the retention of 12 critical enablers based on expert consensus. These enablers were then organized into a hierarchical model using ISM, revealing a layered structure ranging from foundational infrastructure to operational outcomes. The model underscores the need for organizations to first invest in scalable infrastructure, interoperability, and standardization before expecting improvements in traceability, smart contract performance, and consensus mechanisms.

The subsequent MICMAC analysis further classified the enablers into drivers, linkages, and dependents. This classification highlights the dynamic role of certain enablers that not only influence the system but are also influenced by it—requiring careful coordination and management. Notably, enablers such as *System Integration with Legacy Infrastructure* and *Scalability of Blockchain Platforms* emerged as strategic levers with high driving power, while *Auditability and Traceability of Transactions* and *Consensus Mechanism Efficiency* were identified as dependent outcomes of systemic maturity.

This integrated analysis offers both theoretical advancement and practical utility. For scholars, the study provides a structured and empirically grounded model that can inform future research on blockchain adoption in complex industrial settings. For practitioners, the findings offer actionable insights into prioritizing technological investments and sequencing implementation efforts for maximum impact.

While this study offers significant contributions, it also opens up several avenues for future inquiry. First, the current analysis focused exclusively on technological enablers. Future research could extend the model by incorporating organizational and environmental factors, adopting a more holistic view using frameworks like the TOE (Technology–Organization–Environment) or the extended TAM.

Second, the data for this study was collected through expert elicitation and modeled using interpretive techniques. While this enhances depth, it may benefit from complementing with large-scale survey-based validation or simulation techniques to generalize findings across different geographies and supply chain contexts.

Third, the hierarchical structure derived from ISM represents static relationships. Future studies could apply system dynamics or agent-based modeling to explore the temporal evolution and feedback loops inherent in digital transformation projects.
Lastly, sectoral comparative studies—between automotive, healthcare, logistics, and manufacturing—could offer valuable insights into how blockchain adoption enablers differ across industries with varying regulatory and operational environments.

In summary, this study lays a strong foundation for strategic blockchain integration in the automotive supply chain while offering a pathway for future academic exploration and practical execution.

References

Bai, C. and Sarkis, J., A supply chain transparency and sustainability technology appraisal model for blockchain technology, *International Journal of Production Research*, vol. 58, no. 7, pp. 2142–2162, 2020.

Casino, F., Dasaklis, T. K. and Patsakis, C., A systematic literature review of blockchain-based applications: Current status, classification and open issues, *Telecommunications Systems*, vol. 72, no. 1, pp. 1–23, 2019.

Chauhan, A. and Rani, M. V., Comparative insights: Untangling IoT success factors in traditional versus electric vehicle manufacturers, *IEEE Transactions on Engineering Management*, vol. 71, pp. 11282–11296, 2024.

Chauhan, A. and Rani, M. V., Unlocking IoT potential: A holistic analysis of implementation success in automotive supply chains, *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 6–10, Bangkok, Thailand, December 2024.

Chauhan, A. and Rani, M. V., Strategic insights into blockchain adoption in automotive supply chains: A comparative AHP-TOPSIS and TISM-MICMAC analysis, *International Journal of Mathematical, Engineering and Management Sciences*, vol. 10, no. 3, pp. 618–634, 2025.

Chen, S. and Hwang, C., *Fuzzy multiple attribute decision making: Methods and applications*, Springer, 1992.

Christidis, K. and Devetsikiotis, M., Blockchains and smart contracts for the Internet of Things, *IEEE Access*, vol. 4, pp. 2292–2303, 2016.

Dasaklis, T. K., Voutsinas, T. G., Tsoulfas, G. T. and Casino, F., A systematic literature review of blockchain-enabled supply chain traceability implementations, *Sustainability*, vol. 14, no. 4, p. 2439, 2022.

Francisco, K. and Swanson, D., The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency, *Logistics*, vol. 2, no. 1, p. 2, 2018.

Hsu, C. and Sandford, B. A., The Delphi technique: Making sense of consensus, *Practical Assessment, Research & Evaluation*, vol. 12, no. 10, pp. 1–8, 2007.

Ishikawa, A., Amagasa, M., Shiga, T., Tomizawa, G., Tatsuta, R. and Mieno, H., The max–min Delphi method and fuzzy Delphi method via fuzzy integration, *Fuzzy Sets and Systems*, vol. 55, no. 3, pp. 241–253, 1993.

Kamble, S. S., Gunasekaran, A. and Dhone, N. C., Industry 4.0 and lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies, *International Journal of Production Research*, vol. 58, no. 5, pp. 1319–1337, 2019.

Queiroz, M. M., Telles, R. and Bonilla, S. H., Blockchain adoption in supply chain management: Empirical evidence from an emerging economy, *International Journal of Operations & Production Management*, vol. 39, no. 6/7/8, pp. 816–838, 2019.

Saberi, S., Kouhizadeh, M., Sarkis, J. and Shen, L., Blockchain technology and its relationships to sustainable supply chain management, *International Journal of Production Research*, vol. 57, no. 7, pp. 2117–2135, 2019.
Sushil, Interpretive structural modeling (ISM): A tool for strategic decision making, *Global Journal of Flexible Systems Management*, vol. 13, no. 1, pp. 11–18, 2012.
Wang, Y., Han, J. H. and Beynon-Davies, P., Understanding blockchain technology for future supply chains: A systematic literature review and research agenda, *Supply Chain Management: An International Journal*, vol. 25, no. 2, pp. 241–265, 2020.
Warfield, J. N., Developing interconnection matrices in structural modeling, *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 4, no. 1, pp. 81–87, 1974.
Wissuwa, F. and Durach, C. F., Turning German automotive supply chains into sponsors for sustainability, *Production Planning & Control*, vol. 34, no. 2, pp. 159–172, 2023.
Yoo, S. and Won, D., Blockchain-based secure firmware update for embedded devices in an Internet of Things environment, *The Journal of Supercomputing*, vol. 74, no. 7, pp. 3019–3033, 2018.
Zheng, Z., Xie, S., Dai, H., Chen, X. and Wang, H., An overview of blockchain technology: Architecture, consensus, and future trends, *IEEE Transactions on Industrial Informatics*, vol. 15, no. 6, pp. 2316–2326, 2020.

Biographies

Avinash Chauhan is a Doctoral Researcher in Operations and Supply Chain Management at the Indian Institute of Technology Kharagpur, India. His research focuses on the digital transformation of automotive supply chains, with expertise in blockchain, IoT, and decision analytics. He has published in leading journals such as *IEEE Transactions on Engineering Management* and the *International Journal of Mathematical, Engineering and Management Sciences*, with several manuscripts under review in A* and Q1 journals including *EJOR* and *Journal of Operations Management*. He has presented at international conferences including IEEE IEEM, EURO, and INFORMS. Prior to his Ph.D., he worked as a Research Associate at BIS Research, contributing to market analysis in the MedTech sector. His academic work combines methodological rigor with practical relevance, particularly in blockchain adoption, supply chain risk, and sustainable digital systems.

Prof. (Dr.) M. Vimala Rani obtained her Ph.D. degree in Operations Management from the Indian Institute of Science (IISc), Bangalore. She has received a Gold medal and the Best Ph.D. thesis award from the council of IISc. After her Ph.D., she worked as IISc Research Associate at the Department of Management Studies, IISc. She also worked as an Assistant Professor at Amrita School of Business, Bangalore. She has offered Production and Operation Management, Supply Chain Management, Quantitative Techniques-1, Spreadsheet Modelling and Programming for Business to Master Students. Her research interest pertains to developing mathematical and heuristic optimization for the problems related to Management; IoT and blockchain in Port logistics and supply chain management; Humanitarian supply chain optimization; Clinical decision support system in Mental healthcare.