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Strategic Insights into Blockchain Adoption in Automotive Supply Chains: A Comparative AHP-TOPSIS and TISM-MICMAC Analysis

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Abstract
In a highly complex, globally dispersed, and strictly regulated industry such as the automotive supply chain, blockchain technology offers fertile ground to address long-standing inefficiencies and security concerns. Integration of blockchain technology can provide transformative benefits in the form of increased transparency, traceability, security, and operational efficiency. These are the critical elements that will help overcome problems such as counterfeiting, regulatory compliance, and real-time data accuracy, thereby leading to reduced operational costs and resilience in the supply chain. The current study aims to investigate the core facilitators of adopting blockchain technology within the automotive supply chain, using a multidisciplinary approach that involves the application of TISM, MICMAC analysis, and AHP with TOPSIS analysis. Using expert assessments and empirical evidence, this research outlines crucial enablers-increased transparency and traceability, improved security, cost benefits, and operational excellence-as crucial for the acceptance of blockchain technology. Standardization, interoperability, and governance frameworks are equally emphasized to support successful adoption. Results demonstrate the transformational ability of blockchain in modernizing the automotive supply chain management; they offer much-needed insight to practitioners and executives about how best to integrate such a solution into the strategic plans.

Keywords- Blockchain, Automotive industry, Enablers, AHP-TOPSIS, TISM-MICMAC.

1. Introduction

A supply chain represents a multifaceted system that includes all phases of production and distribution, ranging from the acquisition of raw materials to the delivery of finished goods to end-users. The principal aim of this system is to establish a cohesive network of stakeholders that can address diverse customer requirements and enhance responsiveness in the contemporary global economy (Mol, 2003). As the automotive sector transitions to Industry 4.0, characterized by higher levels of automation and increased data exchange, rising demands for instant data and decentralized trust frameworks expose limitations in traditional systems, thus calling for the integration of blockchain technology. Blockchain provides a safe and transparent environment for the management of data and automates processes through smart contracts (McBee & Wilcox, 2020). Smart contracts are self-executing agreements that have stipulations in the form of software: they improve supply chain management through the reduction of the intermediaries and the chances of human errors (Christidis & Devetsikiotis, 2016).

Declining barriers to globalization and the increasing pressure on regulatory policies have witnessed the integration of blockchain technology into the supply chain and automotive industry in a bid for transparency, tress ability, and efficiency. For instance, General Motors has been reported to have developed its own blockchain in order to track parts across all cars produced and thus eliminate counterfeit components as well as making the procedures the company had for recall easier (Azevedo et al., 2023). Also, the BMW blockchain affirms the responsible sourcing of raw materials; it upholds the tenets of sustainability whilst giving credible assurance as to the source of the commodities being sourced (Bouras et al., 2023). During the course of the study, Perboli et al. (2018) noted the Ford pilot project on emissions measurement, which relied on blockchain based system to be an effort on making sure that the environment is not polluted as much emissions were ignored. More specifically, Toyota has attempted to implement a program for enhancing the usage data of automobiles with the help of blockchain technology, as this will optimize other relevant services such as maintenance, insurance, and reselling for Toyota customers. This enables Toyota to give its clients accurate information on the used vehicle's record while safeguarding the vehicle data, thereby eliminating fraud and instilling faith in the used car economy (Dobrovnik et al., 2018). Likewise, in its efforts to improve operational efficiency, Daimler AG has employed blockchain technology to implement payments in machine-to-machine systems, automating the payment of electric cars charging and toll gates (Islam et al., 2022). Volvo, too, applies blockchain principles to adopt principles that guarantee 'conflict-minerals-free' sources for cobalt in batteries of electric vehicles. Tracking, therefore, can effectively be prevented in this complete chain of sourcing for any cases of minerals usage because of keeping them entirely traceable by this very technology-for instance, Xu et al. (2019). However, such full potential would require a further understanding of enablers driving the adoption of blockchain technology and how these interdepend, a topic this paper seeks to address.

Although blockchain adoption has been studied in a wide variety of supply chains, its particular challenges and opportunities in the automotive industry have not been studied to their full extent. This work is unique in the sense that it establishes the enablers of blockchain adoption, and also determines their contextual interactions and dependencies while simultaneously being more relevant and applicable to the specific context of the automotive supply chain. Recent studies, such as Chen et al. (2020) and Makhdoom et al. (2018), have been primarily focused on the promise that blockchain may create in concept to enhance the transparency and productivity. In many cases, however, such theoretical discussions are scarce as to their empirical support in terms of this particular context of the automotive industry, including the interdependence of facilitators such as data privacy, interoperability, and organizational preparedness. The present research is employing AHP, TOPSIS, TISM, and MICMAC to analyze these enablers systematically. In addition to this, this work not only gives emphasis on enablers but also constructs a hierarchical structure to analyze their driving and dependent factors which has not yet been done before.

McBee & Wilcox (2020) noted that blockchain, when integrated with IoT, enhances traceability and data integrity within supply chains by leveraging decentralized, immutable ledgers. The real-time data collection from IoT devices ensures accurate tracking of materials and components, enabling supply chain stakeholders to maintain transparent and tamper-proof records of product movements. This integration mitigates security risks, improves operational efficiency, and fosters trust among participants by ensuring that transactional data remains secure and verifiable throughout the supply chain. This type of data becomes more reliable when stored in a blockchain securely, consequently the interconnectivity can be used to build trust among the actors in supply chains (Kshetri, 2018). These challenges in the fast-developing automotive industry, with increasing and diversified interconnections and interdependencies, have to be met through applying blockchain technology as a decentralized management solution. The enhancements in the security attributes; unalterable tracking mechanism; and clear data qualities of blockchain makes the platform an imperative for meeting regulations and developing confidence in international supply chains. For instance, automotive car-parts tracking platforms that are based on blockchain guarantee that the parts used in autos manufacturing are genuine and check out for the unauthorized entry of counterfeit products (Abeyratne & Monfared, 2016; Saberi et al., 2019).

On manufacturing automobiles, the blockchain has the potential to deliver a strategic advantage from supply chain vulnerability through adaptability. Supply chain responsiveness can be explained as the ability to anticipate, mitigate, and recover from disruptions plausibly and with reasonable speed whereas responsiveness can be assessed as the extent to which, or timeliness with which, it is possible to make changes regarding shifts in demand or changes in the supply situation (Christopher and Holweg, 2011). Blockchain provides real-time transparency of the supply chain actions, enable fast decision making, and implement better coordination between the supply chain members (Bader et al., 2021; Chen et al., 2020). Another way that blockchain can be used is for instance through Jaguar Land Rover's programme that pays drivers in cryptocurrency for sharing data about their automobiles, thus, there is an example of a way that blockchain can be used to encourage consumer involvement and, at the same time, make the supply chain more responsive (Brown et al., 2010). Even though the blockchain is a new technology, it is receiving remarkable academic interest with regards to its use in the automotive supply chain; it provides reliability, efficiency and security (Bader et al., 2021; Chen et al., 2017). For example, Chen et al. (2020) proposed that the adoption of blockchain can enhance the traceability and transparency; and therefore, establishing higher level of trust and reduce operational cost among the stakeholders. In the same way, (Makhdoom et al., 2018) explain how supply chain can improve through the utilization of blockchain technology since it reduces the likelihood of transactions being mediated by human actors.

The purpose of this research is to understand what enablers allow blockchain to be deployed in the context of the automotive supply chain, with a focus on how blockchain addresses pain points that this industry experiences in relation to transparency, traceability, and productivity. Since significant potential has been observed regarding the use of blockchain technology, there has been a lack of proper experimental studies on its use regarding supply chains in auto sectors. The literature in the previous studies largely drew heavily on theoretical model and relatively simple supply chain configurations and many unknowns remain regarding what exactly facilitates or inhibits adoption; especially in auto-related industries (Mougayar, 2016; Tapscott & Tapscott, 2016).

Therefore, by identifying and analyzing the main enablers of blockchain adoption in the automotive supply chain, this study seeks to provide practical recommendations for professionals to improve organizational performance, innovation, and competitiveness in a dynamic market environment.

This study framed the following research questions:

***RQ*1: What are the key enablers of blockchain adoption in the automobile industry, and how do they impact successful integration?**

Previous work investigating the use of blockchain in SCM has mainly centered on general enablers, but there is no relevant conceptualization of opportunities specific to the automotive sector (Wissuwa & Durach, 2021). Automotive industry has a very large intricate, global, and highly regulated supply chain network (Christopher & Holweg, 2011). Such factors provide specific adoption dimensions in blockchain such as, standardization, Interoperability, and data privacy as discussed by Chen et al. (2020) and Bader et al. (2021). Standardisation of an automotive supply chain is also highly critical because the supply chain consist of linked chain members such as manufacturers, suppliers, logistics providers and the regulatory agency. Blockchain also has the ability to function as a standardizer since it supports one structure of recording and sharing information while guaranteeing that all the involved stakeholders receive similar and correct information (Saberi et al., 2019). The other major enabler is Interoperability; this is the ability of interconnected systems and varying organizations to work efficiently. Blockchain support interoperation for supply chain through allowing participants to have decentralized and secure means of sharing data hence enhancing communication and cooperation (Chen et al., 2020). Data privacy also is a concern, as such information may include intellectual properties, trade secrets or personal data. Blockchain can well address the factor of data privacy using strong cryptography and permission or consensus-based mechanisms to allow access or modification only by a selected category of users (Makhdoom et al., 2018). For instance, smart contracts can help to prevent unauthorized access to design plans of new vehicle models and protect a manufacturer's information (Chen et al., 2020).

Moreover, adoption in the automotive industry means some of the enablers including data security, interoperability, smart contract management, blockchain-savvy leadership, efficient partner onboarding, well-developed governance frameworks, readiness in organization, ethical implications, and learning culture (Beck et al., 2018). Data security will make sure that only authorized personnel accesses data of great concern while Interoperability will make sure that different hospitals work hand in hand. Smart contract management brings effectiveness in managing processes and making them automatic. Adoption is facilitated by leadership while integration of stakeholders is done through partner onboarding and compliance is done through governance frameworks. Organizational readiness deals with the capabilities and the ethical perspective under privacy, security, and environmental compliance (Bader et al., 2021; Chen et al., 2020).

***RQ*2: What is the contextual relationship and interdependence among these key enablers in the automobile sector?**
Previous literature review on enablers of blockchain adoption established in this study reveal that prior literature has not considered the context of relationships and interconnectedness of enablers (Agi, 2022). Enablers do not have a direct and separate effect on the adoption of blockchain technology. Some factors may act as complements or substitutes and the effect of a certain factor may vary with specific supply chain context (Mol, 2003). These are important relationship that calls for a better understanding in order to properly strategize for blockchain adoption. This will also aid in the examination of dependence and driving power of the attributes that will spur the use of blockchain.

***RQ*2(a):** To what extent are the identified factors contextual, and how can a hierarchy be used to represent them?

***RQ*2(b):** What is the nature of dependence and driving power of the identified factors that affect the adoption of blockchain technology?

To examine the research questions RQ1 and RQ2, the study employs AHP, TOPSIS, TISM, and MICMAC for evaluating the blockchain enablers based on expert opinions and data analysis. AHP is a method of structuring and evaluating decisions since it is based on the mathematics and psychology of human judgments (Saaty, 1980). TOPSIS selects solutions based on geometric closeness to an ideal solution (Hwang & Yoon, 1981). TISM develops a hierarchical structure of components based on their contextual interlinkages (Sushil, 2012). MICMAC analyzes the driving and dependence powers of variables to understand their influence on the system (Godet, 1976).

This research will, therefore, enhance scholarly discourse as well as industry practice through analyzing the factors that foster the adoption of blockchain technology, while highlighting the necessary ingredients for successful blockchain integration within the automotive supply chain. Moreover, this research will provide industry professionals with practical recommendations. The outcomes of this research will enable industry practitioners and policymakers to make informed decisions about strategies for blockchain adoption, thus deepening our understanding of blockchain's capabilities in supply chain management. This paper contributes to the ever-growing literature on blockchain technology adoption and offers a sound foundation for further research on this trend.

2. Literature Review

The automotive world, being very complex with huge production costs, has a great need for high-quality control processes to meet consumer demand as well as social expectation. The diversified supply chain in the automotive world, comprising several tiers of suppliers, makes it challenging but highly necessary for quality assurance (Christopher & Holweg, 2011). Since the organization's products are produced in several geographical locations and depends heavily on its upstream supply chain partners, it has been challenging to attain consistent quality across the different layers of production (Steven et al., 2014). The current disruptive technology known as the blockchain that was originally designed as the base structure for Bitcoins implemented by Nakamoto (2008) has turned out to be an ideal solution to these challenges, especially concerning supply chain issues such as traceability, transparency and trust.

Recently, the automotive industry has taken a hunch on the probability of blockchain technology. Treiblmaier (2018) in his research found it to have the capability of impacting supply chain relations by offering a secure, open and tamper proof system of tracking products and information. Thus, this innovation could address some of the key issues that was identified in the automotive supply chain including counterfeit parts, late deliveries, and inadequate visibility in multi-tier supplier systems. Kamble et al. (2020) discussed the ability of blockchain in integrating supply chain supply chain, enhances operational efficiency and enables sustainable goals. The authors found out that transparency through blockchain technology leads to trust and traceability and enables quality assurance in automobiles.

Gurtu & Johny (2019) provided a detailed review of literature on the potential of blockchain technology for supply chain management (SCM) in industries such as the automotive sector. The authors pointed out that while blockchain technology possesses considerable strengths such as increased transparency, removal of intermediaries, and increased traceability, its mass adoption is still limited. Some of the main limitations identified are the lack of standardized protocols, complexity in integration with the existing enterprise infrastructure, and enormous financial investments involved in creating blockchain-based infrastructure. Notwithstanding the limitations, the research emphasized blockchain's capability to revolutionize supply chain operations through real-time sharing of data, minimization of transactional risk, and security in the supply chain. The authors noted that the combination of blockchain with other technologies like the Internet of Things (IoT) would enhance supply chain resilience by offering automated verification mechanisms and permanent transaction records.

Wang et al. (2019) detailed the extent that blockchain technology can be applied in the area of supply chains. Blockchain has the potential to impact existing supply chain operations. Blockchain can significantly make supply chains work better by using smart contracts to automate tasks as well as improve data security. This is very much important for the automotive sector. The automotive sector needs dependable and real-time data for taking care of complex supply network chains.

Paliwal et al. (2020) made a demonstration of the possible various uses of blockchain to ensure the traceability of products in a study concerning food supply chains. While they primarily speak about the food industry, these ideas related to traceability and transparency might also be applied within the context of the automotive sector where blockchain will help in providing confirmation that parts are legitimate and which path they undergo within the supply chain. Kshetri (2018) pointed out that blockchain is going to improve the way the business works and tracks products for the automotive industry, which may ensure quality. Kang et al. (2019) mentioned that blockchain can let electric vehicles trade electricity directly between each other, showing how beneficial this technology can be in the automobile field. In their work, they display how blockchain can create decentralized networks that improve how things are done and support new business ideas in an automotive ecosystem.

Saberi et al. (2018) examined the link between blockchain technology and sustainable supply chain management while recognizing blockchain as a key driver of sustainability initiatives. Their findings are highly significant for the automotive industry, which, at present, is experiencing mounting pressure to become more environmentally friendly. Blockchain as a solution to achieve environmental objectives can be invaluable to automotive firms because it allows for recording environmental impact data in a transparent and protected manner that can meet regulatory compliance. Following up on the sustainability potential of blockchain, (Ayan et al., 2022) carried out a review to further assert the reality of blockchain in transforming sustainable supply chains through better communication, tracking, and responsibility. Chang et al. (2019) explained the concept of blockchain for redesigning business processes and proved that it can be very useful in cutting down costs, making processes lean and creating a perfect integration in global operations mostly in the automobile industry's supply chain system.

While drawing on the sustainability benefits of blockchain technology, Chang et al. (2019) went further to explore how blockchain can impact business process change in international trade. Their conclusion shows how similar principles improve operating efficiency within the car supply chain. Automobile producers involved in dealing with complex networks gain a lot from blockchain due to its ability to reduce costs, eliminate inefficiencies, and enable seamless cross-border operations.

However, the application of blockchain technology within any sector has its own complexities with the effectiveness of its use. Sharma et al. (2023) also embarked on a systematic review on blockchain adoption which elaborated on the enablers and the challenges experienced in various sectors. Challenges including scalability, compliance with regulations, and integration of systems are critical in automotive manufacturing segment to realise the potential of blockchain. Intelligent transportation systems, which are highly relevant to the automotive industry, were discussed by Yuan and Wang in terms of the application of blockchain technology in 2018. Their work highlighted the potential of blockchain in enhancing data protection and privacy in V2V communication which is critical for the development of autonomous and connected vehicle technology areas that automotive industry is seeing significant progress.

Further expanding on the technological applications, Yuan & Wang (2018) considered the importance of blockchain in ITS systems that are inextricably connected with the automotive industry. They specifically emphasized that their work was aimed at revealing the fact that blockchain technology can improve the security and privacy of V2V communication, which is one of the key factors in the further development of autonomous and connected vehicles - a field in which the automotive industry is rapidly evolving.

Out of all these enablers, two have emerged most often in consideration of this interest in adoption: they are transparency and traceability. Blockchain will guarantee that products move from one point to another without hitches hence reducing fraudulent and erroneous deals (Crosby et al., 2016). Of these, the automotive sector is most relevant to the concept of authenticity with regard to the product and its quality. To build on the literature review, it is necessary to incorporate other performance models that are relevant to applications of blockchain in supply chain. For example, Saberi et al. (2018) examined the use of blockchain in sustainable supply chain management to argue that blockchain technology improves on transparency and traceability, two crucial factors that can be used to check quality in automobile production. In their research, the authors concluded that application of blockchain technology can help implement secure records that will prove the origin of a product to reduce risks of having fake parts. Besides this, Wang et al. (2019) used a systematic literature review that points out the potential of blockchain to significantly enhance the performance of the supply chain.

Specifically, when it comes to handling complicated supply chain networks of the automotive industry this application elaborates on the use of smart contracts for automating processes in the technology. Kshetri (2018) also writes on how blockchain can be used to help with product traceability and posits that it may only provide a decentralized solution to making operational efficiency even more efficient. The same idea is used in a study by Queiroz & Wamba (2019) which discusses the challenges and opportunities of using blockchain in supply chains with focus on its real-time visibility and reliable data sharing. However, the research papers stress that standardization and interoperability should be achieved to promote the successful implementation of blockchain technology in the supply chain. In their study, Zhao et al. (2019) posited that standardisation should be adopted for the purpose of achieving interoperability of different blockchain systems, particularly in multi-continental industries such as the automobile industry. This was also supported by Dolgui et al. (2020), who noted that to address interoperability challenges, comprehensive industry standards have to be created.

Another issue that may help to explain the effectiveness of the blockchain technology application is the trust between supply chain members. (Hughes et al., 2019) explain that thanks to blockchain, trust is built through the distributed ledger that eliminates middlemen and provides collaboration. This level of trust can lead to effective working, reduced expenses and improved quality and timing within the automotive manufacturing environment. Furthermore, (Ali et al., 2019) stressed that the integration of blockchain with the devices of the Internet of Things, increases the real-time visibility of the supply chain processes. This facilitates accurate monitoring and keeps records for it which cannot be interfered with. These innovations contain the realistic approaches to addressing most of the automotive industry's perennial challenges. The cryptographic security attributes strengthen the protection of blockchain technology against data and cyber-attacks (Chen et al., 2020) making supply chain processes secured and increasing confidence among the players. However, the literature review reveals that there is lack of standards and lack of integration to support the efficient adoption of blockchain in supply chain systems. Through standardization, more stakeholders can be reached and the supply chain made even more efficient by incorporating different blockchain platforms (Chen et al., 2020). This is very significant for the automotive industry because the chain has a large number of players and is spread over a large geographical area. In this context, standardisation can play a large role in contributing to technical barriers to the wider use of blockchain technology (Bader et al., 2021).

Apart from the technical factors, what is equally equally critical for the implementation of the blockchain technology is the trust and co-ordination within the supply chain network. The essence of blockchain technology – being open and consistent – enhances the confidence of the participating parties and minimizes the need to engage intermediaries and promotes direct interaction (Saberi et al., 2018). In the context of automobile industry, it means that there would be higher operating efficiency, lower costs, more efficient and effective quality and timely delivery of its product (Crosby et al., 2016). To elaborate on these enablers, qualitative as well as quantitative research studies have used different methodological techniques. In hierarchical relationship, Total Interpretive Structural Modeling (TISM) facilitates the position of enablers, while in driving power and dependence, Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) analysis gives the solution (Mol, 2003). Besides this, based on the expert judgments, Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) provide the framework in terms of measuring relative importance of enablers. These methods give significant information about the most relevant factors influencing the blockchain adoption and their interaction. By additional development of the given literature body of this study, it tries to supply the desired analysis of the facilitators of blockchain in the supply automotive chain and simultaneously the useful suggestions for the industrial policymakers as well. In this research, the antecedent factors of blockchain implementation in the automotive supply chain were established through a systematic literature review and interviews with professionals from the automotive industry. The understanding achieved is shown in **Table 1** (Blockchain Enablers), which provides an outline of factors that can promote the implementation of the blockchain in the automotive industry.

3. Methodology

Overall, three phases are followed in terms of the research methodology. Firstly, enablers were identified through systematic literature reviews and structured interviews with industry experts. The literature was able to produce 20 enablers, which were later refined through expert feedback and identified 12 enablers specific to the automotive sector. The PESTLE framework was then used for further categorization of enablers along the lines of Political, Economic, Social, Technological, Legal, and Environmental dimensions so that all aspects could be included.

The subsequent phase emphasizes the gathering of data, during which systematically designed surveys were disseminated to meticulously chosen specialists occupying leadership positions within the automotive and technology industries. The selection of these specialists was based on rigorous criteria, necessitating a minimum of five years of professional experience and proficiency in areas such as blockchain, IoT, or supply chain management (Chauhan & Rani, 2024). Participants were included only if their normalized weights exceeded 0.75, thereby guaranteeing a dataset of significant credibility. Using a Likert scale, specialists rated the significance and effect of every facilitator that can make important contributions in the later analysis.

The multi-criteria decision-making (MCDM) techniques were finally applied for rating the identified enablers during the final stage of evaluation. The AHP technique was utilized in order to compute the relative importance of enablers while ranking is done using TOPSIS which ranks the enablers depending on their relative efficacy when compared with an ideal solution. To gain a better insight into the interlinkages between the enablers, Total Interpretive Structural Modeling was conducted to generate a hierarchical model that brings out key drivers and dependent variables. MICMAC analysis simultaneously classified enablers into four types of variables: Independent, Dependent, Linkage, and Autonomous variables, and therefore provides a holistic view of interdependencies among them.

This three-stage methodology is graphically represented in **Figure 1**, which clearly explains the step involved-from the identification of enablers to data collection through advanced analyses with MCDM techniques. The following sections explain the three stages in detail.

3.1 Phase 1: Identification of Blockchain Enablers

The study systematically reviewed existing literature and conducted structured interviews with experts to identify factors affecting blockchain adoption in the automotive sector. This research involved a comprehensive database search using relevant keywords, resulting in the identification of 20 enablers from the literature. Subsequent interviews with automotive professionals revealed 12 enablers. **Table 1** summarizes the 12 enablers respectively specific to the automotive industry, as discovered in Phase 1 of the study.

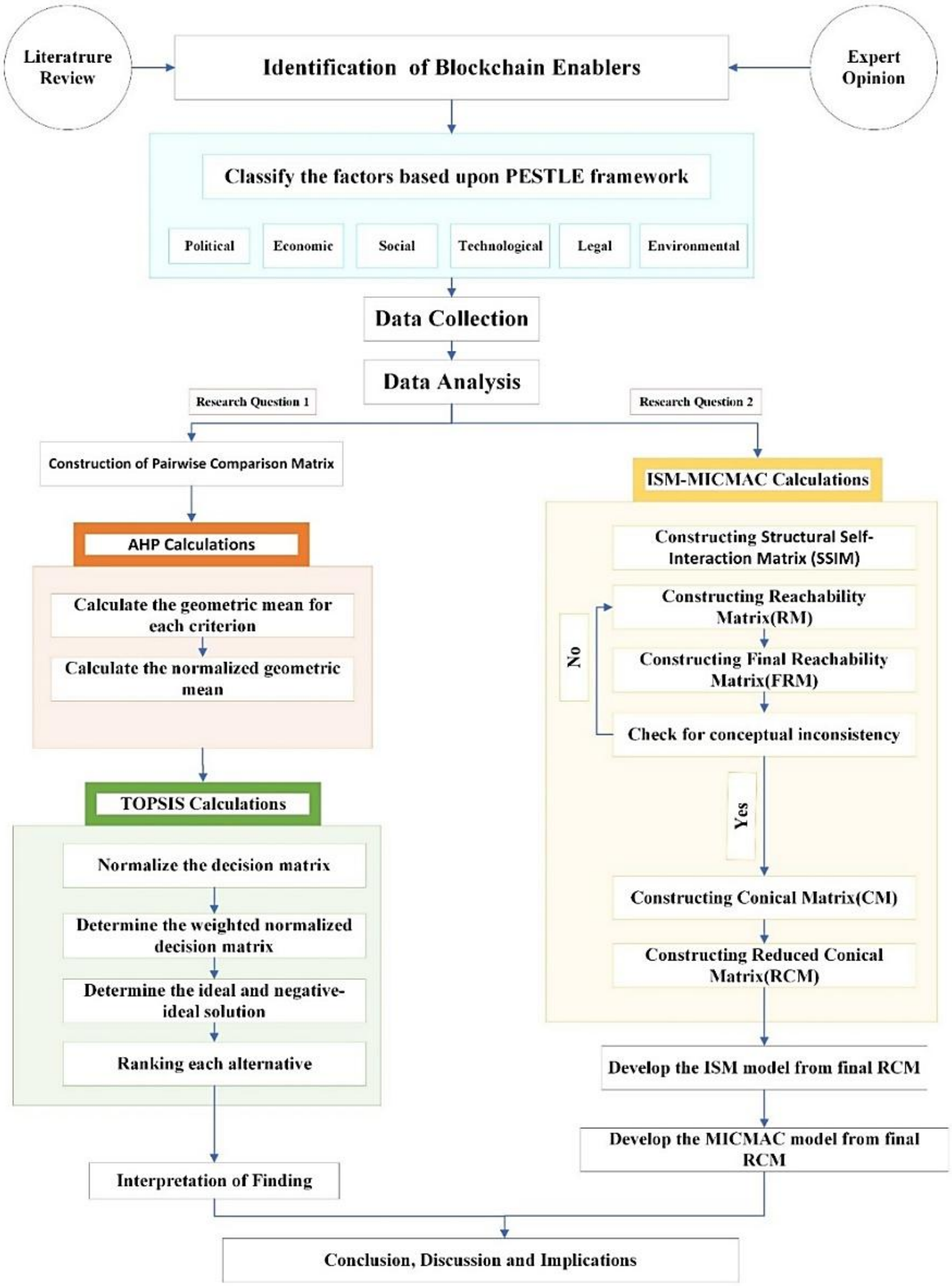

Figure 1. Research methodology conceptual model.

Table 1. Enablers of blockchain adoption in automobile supply chain.

Dimension	Enabler	Explanation (Reference)
Political	Compliance and regulatory requirements	Being irreversible, blockchain transaction records establish a verifiable audit trail with which businesses can comply for examples such as Know Your Customer (KYC) or Anti-Money Laundering (AML). Thereby, this enables regulated oversight, promotes responsible conduct, and safeguards against money laundering and other financial frauds (Alshamsi et al., 2022; Casino et al., 2019).
Economic	Improved supply chain management and logistics	Blockchain offers real-time visibility into the movement of goods and services. A business can identify bottlenecks, optimize supply chains to ensure timely deliveries. Consequently, this enhances supply chain efficiency as well as reduces delays for logistics management (Alshamsi et al., 2022; Saberi et al., 2018).
	Increased automation and operational efficiency	The automation of such manual processes as invoice payments, shipment tracking, and reconciliation of data makes operations efficient, eliminates human error, and reduces administrative costs. This makes the processes more efficient and productive, while also allowing for better resource allocation (Clohessy & Acton, 2019; Korpela et al., 2017; Zhao et al., 2019).
Social	Increased trust and collaboration	With a blockchain-based secure and transparent data-sharing platform, companies are able to collaborate and share supply chain data while combating counterfeit products and enhancing the product development process in an environment of trust (Brown et al., 2010; Zhao et al., 2019).
	Improved quality control and product authentication	Blockchain tracks the products from their production to the end user by ensuring quality and authenticity of that product. Business can monitor temperature, handling conditions, etc. while shipping the product; pharmaceuticals would remain potent and other products would have the quality standards (Shrestha & Vassileva, 2019; Tseng et al., 2018).
	Customer satisfaction and loyalty	Blockchain's ability to provide transparency and control over data empowers customers, fostering trust and loyalty. Customers can access transaction records, track the movement of goods, and verify product authenticity, building confidence in the brands they interact with (Clohessy & Acton, 2019; Xiang et al., 2024).
Technological	Improved transparency and traceability	The tamper-proof records of transactions which blockchain offers facilitate tracking right from raw material sourcing till final delivery within the complicated automotive supply chain. This is how companies are able to source materials ethically, prove authenticity, and avoid counterfeits (Francisco & Swanson, 2018; Hew et al., 2020).
	Enhanced security	Cyber threats are continually changing, and blockchain becomes a powerful tool for preventing unauthorized access and data breaches. Being decentralized and having cryptographic algorithms, the blockchain records become almost impossible to change. The sensitive information gets protected along with the fact that the data stays intact (Clohessy & Acton, 2019; Tapscott & Tapscott, 2016).
	Better efficiency and cost savings	Blockchain automates manual processes such as record-keeping, reconciliation, and invoice processing, which streamlines operations, reduces administrative burdens, and eliminates costly errors. Time and cost savings are enormous, so that overall operational efficiency is greatly improved (Ivanov et al., 2019; Ullah et al., 2020).
	Innovation and competitive advantage	Blockchain flexibility contributes to innovation, which makes business push the new financial tool designs, develop innovative ideas for tracking the inventory, and explore some of the revolutionary applications related to autonomous cars and smart vehicles (Clohessy & Acton, 2019; Nofer et al., 2017).
Legal	Better risk management and compliance	A blockchain keeps a safe and unchangeable record of transactions. It will help companies get and reduce risks. It supports fraud, reduces theft, and helps manage overall risks. It also aids them in dealing with the rules and regulations (Alshamsi et al., 2022; Gurtu & Johny, 2019).
Environmental	Sustainability and social responsibility	Blockchain can track the environmental impacts of supply chains. It helps businesses reduce their carbon footprint and encourages sustainable practices: it includes tracking the volume of water and energy used, creating better processes in production, and waste reduction (Alshamsi et al., 2022; Saberi et al., 2018).

3.2 Phase 2: Data Collection

To select competent data collection professionals, two criteria were applied: a minimum of five years of professional experience and an undergraduate degree in a relevant field, such as mechanical engineering, supply chain management, blockchain, or project management, along with practical experience in the automotive or supply chain industry. Experts' profiles were assessed using a Likert scale (1 to 5). After normalizing the weights to a 0-1 scale, participants with weights over 0.75 were selected, while those below were excluded. In total, 15 experts were chosen for further analysis. **Figures 2** and **3** show the experts' organizations and their experience with blockchain technology.

Figure 2. Number of responses and expert's organization.

Figure 2 shows the distribution of selected experts from various organisations, highlighting the diversity and trustworthiness of the survey participants 40% of the 15 experts are associated with Skoda Auto, which shows that they are strong representatives of the major automaker. Other participants included organizations such as ARXUM (20%), Infosys Limited (13%), Tata Consultancy Services (7%), Cubeint (7%), Timeline Infosec (7%), Micron Technology (6%) These organizations have a relationship guarantee for that the collected insights include a wide range of expertise, spanning automotive manufacturing, engineering solutions and consulting services.

It was based on a rigorous selection process to ensure that only the most qualified individuals participated. Experts were selected using a standardized weighting system, including only those with scores above 0.75. Each participant has at least five years of experience in a related field such as blockchain, IoT, or supply chain management and holds leadership positions such as assistant general manager, senior manager, and director. This methodological representation not only validates the findings but also provides a comprehensive understanding of blockchain's enabling factors in the automotive supply chain.

Moreover, the collective expert revel in of the specialists' stages from 10 to 25 years, making sure a thorough understanding of present-day challenges and emerging trends within the industry. This big range of expertise lays a solid foundation for insights concerning the mixing of blockchain era in the automobile deliver chain, ensuring that the findings reflect credible, practical applications.

In conclusion, the meticulous selection process and the high caliber of the experts render the collected data highly reliable, despite the limited sample size. The combination of extensive experience, leadership roles, and diverse industry representation guarantees that the analysis yields a comprehensive understanding of blockchain enablers in the automotive sector.

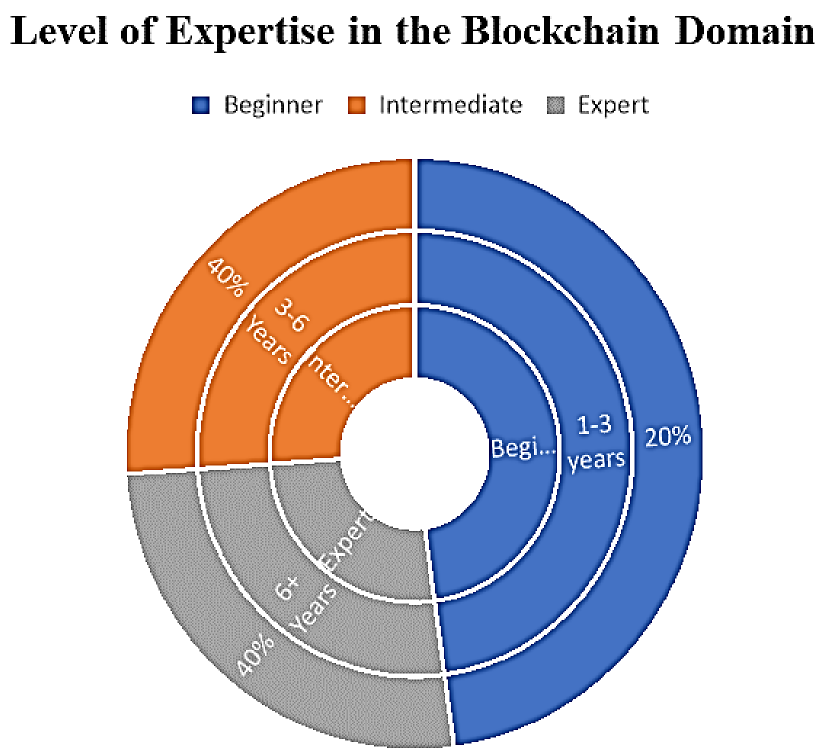

Figure 3. Working experience of the experts.

Figure 3 profiles the respondents' knowledge base about blockchain technology, as divided into three different levels: Beginner (1-3 years), Intermediate (3-6 years), and Expert (6+ years). Interestingly, as many as 40 percent of the respondents are in the Expert category, indicating heavy practical experience and higher consciousness in blockchain use. Another 40 percent fall into the Intermediate category, boasting three to six years of practical experience in the blockchain market. Only 20% of the answers fall into the Novice category, thus guaranteeing that almost all answers come from people with high levels of expertise.

A high number of professionals and intermediaries in the study indicate that statistics collected are reliable. The professionals are aware of the opportunities and challenges with blockchain adoption in the automobile industry, making them necessary for comprehensive analyses such as TISM and MICMAC. Their expertise ensures a diverse range of views in consideration-from strategic decision-making down to technical execution.

The combination of **Figure 2** and **Figure 3** presents the strength of the process of collecting data. This sample size of 15 participants may look small, yet their various organizational backgrounds and leadership experiences ensure that it is substantial enough to credit the results. By selecting experts with practical experience and domain-specific expertise, the study leverages high-quality insights into the integration of blockchain technology in the automotive supply chain.

Additionally, these figures reinforce the study's methodological rigor, showcasing how the selected experts were instrumental in the evaluation and prioritization of blockchain enablers. The distribution of expertise and organizational representation adds a layer of confidence to the study's conclusions, ensuring that they are both reliable and reflective of industry realities.

The questionnaire survey was distributed to these experts via email or face-to-face interactions, comprising two phases: In the first phase, experts rated the importance and impact of each identified enabler for IoT adoption in the automotive industry. They also provided recommendations for leveraging the enablers for successful adoption. In the second phase, the same 15 experts were surveyed again to collect data for TISM and MICMAC analysis. These techniques help identify critical variables and their interrelationships in complex systems. TISM analysis establishes the hierarchy of variables, while MICMAC analysis categorizes variables based on their driving and dependence powers.

3.3 Phase 3: MCDM Methods

This study used various MCDM methods, including AHP, TOPSIS, TISM, and MICMAC. The Analytic Hierarchy Process traces its roots back to Aristotle's pairwise comparisons and Benjamin Franklin's 18th-century formalization in the pro and con list. In the 1970s, Saaty integrated these concepts with psychology and mathematics, initially for military applications. AHP is applied in various areas such as business and government sectors as well. Topology-based technique, namely, TOPSIS was developed in 1981 by Hwang and Yoon and it is used to calculate distances from an ideal and negative ideal solution for a decision with relatively little information available. There are two sophisticated tools that could be employed for the purpose of analysing complex relationships between various factors in a complex system such as enablers for blockchain technology adoption in supply chains – Total Interpretive Structural Modeling (TISM) and Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement (MICMAC). These methodologies provide a framework in identification, classification and analysis of driving power and dependence of such enablers, thus providing an understanding of their hierarchy and dependency. Therefore, following the works of Agarwal et al. (2006), and Mandal & Deshmukh (1994), this study uses an integration of several methodologies to have a proper view of the factors that enable blockchain adoption in the automotive supply chain. Each approach presents unique input in the holistic evaluation and gives multiple perspectives that are essential for appropriate response to the research questions.

The Analytic Hierarchy Process involves putting things in pairs and asking how important they are. This method assists in making see how relevant certain factors are. Using a method like this provides a solid foundation to determine which factors are critical to the adoption of blockchain (Saaty, 1980).

The weights are further used in the Technique for Order of Preference by Similarity to Ideal Solution, or TOPSIS method, which systematically ranks the enablers based on their proximity to an ideal solution. Based on how well each enabler has performed compared to an optimum benchmark, TOPSISIS enables a unique prioritization (Hwang & Yoon, 1981). This combination of AHP and TOPSIS is particularly useful because it can perform a detailed study of the importance of each enabler using AHP and, at the same time, rank by performance through TOPSIS. The problem with using AHP alone is that it concentrates only on the relative importance of the variables without looking into how these enablers perform with respect to some ideal standards.

However, because TOPSIS produces ranking scores, it does not reflect the relative significance of the factors in creating a detailed analysis. From this perspective, when weighted by AHP and then ranked by TOPSIS, the two approaches benefit each other to present the overall assessment of both weights and performance of the enabling factors in an impartial and informative way.

However, while these models are powerful for determining how the most significant enablers are best identified, they do capture interactions and dependencies among all the enablers included in the model. More importantly, understanding these may help reveal underlying causalities and dependencies that influence Blockchain adoption. To address this, TISM models a structured hierarchy that captures interactions and interdependencies of diverse enablers. This way, by TISM, a holistic model could be developed about how diverse enablers interact, influence each other, and play their various roles to facilitate blockchain's adoption process (Sushil, 2012). In this manner, this model results in graphics, as well as exploring hierarchical order and revealing causal interaction relationships not possibly through ranking per se. Understanding such interactions leads to identification of key drivers and dependencies critical for successful blockchain integration.

The Cross-Impact Matrix-Multiplication Applied to a Classification (MICMAC) is a refinement of the analysis in that it classifies enablers by their driving influence and reliance (Godet, 1976). MICMAC categorizes factors into four different categories: autonomous, dependent, linkage, and independent variables. This categorization gives strategic insights about the enablers that exert the highest influence and how they influence other elements. For example, factors that are highly driving but less dependent are of utmost importance for catalytic change, whereas those having high dependence and low driving power may require support from other enablers for effectiveness.

The integration of MICMAC with AHP and TOPSIS allows for a holistic understanding not only of the prioritization of the enablers but also of their strategic relevance and interconnections. This integrated approach ensures thorough analysis by taking into consideration both the importance of every enabler and their interactions with each other. By integrating these two, AHP along with TOPSIS merged with TISM and MICMAC, one understands about the varied factors behind the integration of blockchain. The outcome of this approach ranks, not only on importance versus performance of enablers but also the relation each of the enablers has and how these link to one another. The methodological integration provides rich insights into deciding and developing strategy by ensuring enablers, detailing interactions and dependencies, as well as classifying into enablers for strategic assessment. Each of these MCDM procedures is presented herein.

3.3.1 Analytic Hierarchy Process (AHP) Method

AHP determines criteria weights identified in phase 2. AHP, a decision-making method for subjective or challenging-to-quantify criteria, involves the following steps:

i. ***Calculate Criteria Weights*****:** Compute the geometric mean of each row in the normalized pairwise comparison matrix as per Equation (1)

$$w_i = \sqrt[n]{\prod_{j=1}^{n} Normalized\ pairwise\ comparison\ matrix\ element\ i,j} \tag{1}$$

ii. ***Normalize Geometric Mean for TOPSIS Analysis*****:** Calculate the normalized geometric mean as per Equation (2)

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (2)$$

where, "i" denotes the specific criterion, "j" denotes other compared criteria, "n" is the number of criteria in the analysis.

3.3.2 Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) Method

The procedure includes the following steps:

Step i: Normalize the decision matrix

$$r_{ij}(x) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad i = 1, \ldots, m \;\; ; j = 1, \ldots \;\; , n \quad (3)$$

Step ii: Determine the weighted normalized decision matrix

$$v_{ij}(x) = w_j r_{ij}(x) \quad i = 1, \ldots, m \;\; ; j = 1, \ldots \;\; , n \quad (4)$$

Step iii: Determine the ideal and negative-ideal solutions

$$A^+ = (v_1^+, v_2^+, \ldots, v_n^+) \quad (5)$$

$$A^- = (v_1^-, v_2^-, \ldots, v_n^{-+}) \quad (6)$$

So that,

$$v_j^+ = \{(max\ v_{ij}(x) |\ j\epsilon j_1), (min\ v_{ij}(x) |\ j\epsilon j_2)\}\ \ i = 1, \ldots, m$$, and

$$v_j^- = \{(min\ v_{ij}(x) |\ j\epsilon j_1), (max\ v_{ij}(x) |\ j\epsilon j_2)\}\ \ i = 1, \ldots, m$$

where, j_1 and j_2 denote the negative and positive criteria, respectively.

Step iv: Determine the distance between ideal and negative-ideal solutions

$$S_i^+ = \sqrt{\sum_{j=1}^{n} [v_{ij}(x) - v_j{}^+(x)]^2} \;\; , \;\; i = 1, \ldots, m \quad (7)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} [v_{ij}(x) - v_j{}^-(x)]^2} \;\; , \;\; i = 1, \ldots, m \quad (8)$$

Step v: Ranking each alternative

$$C_i = S_i^- / (S_i^+ + S_i^-) \quad (9)$$

The alternative with the highest C_i value is considered the best option.

3.3.3 TISM (Total Interpretive Structural Modeling) and MICMAC (Matrice d' Impacts Croisés-Multiplication Appliquée á un Classement) Methods

TISM extends the traditional Interpretive Structural Modeling (ISM) by incorporating interpretive logic into the structural modeling process. The method begins with the identification of relevant enablers through expert interviews, literature review, and empirical data, ensuring a comprehensive understanding of all potential factors influencing blockchain adoption (Sage, 1977). After this, the expertise of the system compares pairs of enablers and decides if one enabler affects another, which makes the formation of the Structural Self-Interaction Matrix (SSIM). The next step involves converting the SSIM into reachability matrix which is then fine-tuned to develop the final model of enablers hierarchy and their relationship (Warfield, 1974). This interpretative process also helps in explaining not only the interconnections but the rationale for these connections as well, which give a deeper insight into the dynamics of the system as it is (Janes, 1988).

On the other hand, the MICMAC analysis helps to support TISM by categorizing the enablers by the driving power and dependency. Cross Impact Matrix has to be created, which means that the effect of each enabler has to be assessed on the others following the initial method proposed by Godet (1976). Subsequently, the matrix will be used to identify the driving power and dependence of each enabler and subsequently categorize the enablers into four groups; namely, the Autonomous, Dependents, Linkage, and Independents. Low driving power and dependence represent the fact that autonomous enablers have a small effect on the system. On the other hand, dependent enablers have low driving power together with high dependence, which make them very vulnerable to outside forces. A linkage enabler is defined where there is a high driving power and high dependence, these are the intermediary of the system. Independent enablers, on the other hand, exhibit high driving power in combination with low dependence; they are agents of change within the system of the BTP (Godet, 1986).

By the use of TISM and MICMAC, researchers will be well positioned to determine what facilitates the use of blockchain technology within supply chains. TISM provides a clear hierarchical structure of enablers, while MICMAC divides enablers into the level of interaction and the level of dependency. In turn, this provides a rich understanding of roles and relationships between those enablers (Singh et al., 2007). The research approach and design allow for recognition of other variables that can lead to high levels of blockchain technology adoption, which will in turn assist in the formulation of appropriate decisions and the correct implementation of blockchain (Attri et al., 2013). Much relevant knowledge has been acquired by TISM as well as MICMAC studies for leading industry players and policymakers who are keen to leverage blockchain technology for better efficiency, transparency, and supply chain security (Jain & Raj, 2016).

3.4 Application of the Developed Method

The integration of AHP, TOPSIS, TISM, and MICMAC allows for an all-round structure to assess and support the adoption of blockchain technology within the automotive supply chain. This methodology begins with identifying and ranking the essential enablers through AHP, which uses pair-wise comparisons to determine the relative importance. For instance, a manufacturer that emphasizes the transparency of the supply chain would rank enablers such as data security, interoperability, and the management of smart contracts first. On that basis, TOPSIS will rank these enablers based on how close they are to an ideal solution. Then, it will guide decision-makers on which factors to allocate more resources and implement further. For example, if interoperability is the closest to the desired outcome, it will be the top choice for resource allocation and implementation. TISM is subsequently utilized to illustrate contextual relationships, demonstrating the impact of foundational enablers such as organizational readiness on other elements, including governance frameworks and regulatory compliance. By systematically addressing these interdependencies in a hierarchical fashion, the adoption process is rendered more structured and methodical. MICMAC enhances this analysis by classifying enablers according to their driving power and level of dependence, thus allowing stakeholders to differentiate independent drivers, exemplified by data security, from dependent factors, such as regulatory compliance. This categorization also ensures that organizations become aware of which facilitators can promote blockchain technology adoption independently and which require external support.

The framework can be used in wide, real-life scenarios to apply practically. For example, ethical sourcing, this framework may be used by car manufacturers for highlighting the enablers like traceability and supplier collaboration applying TISM for finding out interdependencies such as how supplier collaboration is responsible for traceability. Similarly, the battle of counterfeit components is all about ranking the enablers like real-time monitoring and smart contract management through AHP and TOPSIS for successful implementation of blockchain-based verification systems. To improve the supply chain visibility, logistics service providers can benefit from classifying enablers, such as IoT integration and interoperability, by using the MICMAC method to formulate specific strategies. The scalability in this framework allows it to be adapted to the scale and complexity of an organization. A small supplier can focus on the most important enablers, while a large multinational enterprise may use the whole framework to develop an all-inclusive strategy for adoption. This holistic multi-method approach bridges the gap between theoretical models and their implementations, resulting in practical insights to improve transparency, traceability, and operational efficiency in the automotive supply chain. The framework addresses the interactions of critical facilitators to empower stakeholders with the necessary tools to effectively manage the complexities of blockchain adoption, thereby fostering increased trust, efficiency, and adherence to regulatory standards.

4. Results and Analysis

Results from this study will indicate which of the critical enablers for blockchain in the automotive supply chain are as per the determination using AHP-TOPSIS and TISM-MICMAC analysis. In essence, these factors are encompassed under technological readiness, stakeholder collaboration, and regulatory support.

4.1 Identifying Key Enablers: AHP and TOPSIS

The procedural steps for both AHP and TOPSIS were the same, those described in the preceding section. Nevertheless, as the report is within words and page distributions, here is a summary of results in this section and, therefore, the whole database and detailed analysis in Annexure 1 (Refer to **Table A1**, **Table B1**, **Table C1 to C3**). This outcome of the analytical procedure is explained in **Table 2**: The conclusive results are aggregated from the AHP and TOPSIS analysis below:

Table 2. Ranking of enablers under each criterion based upon the AHP, and TOPSIS analysis.

Dimension	Dimension weight	Enabler	AHP Weight (%age)	Relative closeness to ideal solution	Ranking
Political	10.089%	Compliance and regulatory requirements	10.089%	0.728	1
Economic	18.421%	Improved supply chain management and logistics	8.897%	0.380	12
		Increased automation and operational efficiency	9.525%	0.587	6
Social	25.039%	Increased trust and collaboration	7.646%	0.493	10
		Improved quality control and product authentication	7.745%	0.505	9
		Customer satisfaction and loyalty	9.648%	0.507	8
Technological	29.452%	Improved transparency and traceability	7.050%	0.690	2
		Enhanced security	8.099%	0.612	5
		Better efficiency and cost savings	8.165%	0.645	3
		Innovation and competitive advantage	6.138%	0.534	7
Legal	8.399%	Better risk management and compliance	8.399%	0.641	4
Environmental	8.600%	Sustainability and social responsibility	8.600%	0.439	11

Using the analysis with AHP and TOPSIS in **Table 2**, ranking and assessment of the enablers of blockchain along the dimensions of political, economic, social, technological, legal, and environmental in ASC. The study reveals that each of the dimensions contributes to blockchain technology adoption remarkably; the most critical driver remains to be the technological dimension in its weight on the decision-making process. In this context, the factors of Improved Transparency and Traceability, Enhanced Security, along with Greater Efficiency and Cost Savings, will be significant facilitators for the adoption of blockchain technology. These technological advancements address several critical issues that are prevalent in traditional supply chains while simultaneously generating advantages that position blockchain as a comprehensive transformative solution. The primary enabler, Enhanced Transparency and Traceability, demonstrates the inherent benefit of blockchain technology: it creates tamper-proof records that enhance trust and accountability along the supply chain. The highest priority of Augmented Security reflects the growing concern with information protection in an economy operating primarily in the digital world, constantly at risk of data breaches and cyberattacks. Furthermore, it highlights that the elimination of intermediaries and the enhancement of processes through blockchain technology provide tangible financial advantages to stakeholders.

Although the political aspect is not as crucial as technological influences, more important assignments to Compliance and Regulatory Requirements suggest that only after stepping through legal structures can blockchain technology be covered. This means the governments and regulatory bodies need to back up the blockchain project in earning its legit and scalability. And so, the involvement of Governments and Regulatory bodies in determining a standard definition would eliminate Adoption Blockages on the idea of Blockchain technology from ASC. In this economic aspect, more automation and improved functional performance is seen with enhanced Supply Chain Management and Logistics. These enablers indicate the potential of blockchain in streamlining operations and increasing the accuracy and timeliness of supply chain activities. Their moderate ranking, however, indicates that while economic gains are essential, technological improvements have a more direct impact on the overall value proposition of blockchain.

Within the social dimension, Customer Satisfaction and Loyalty are of more importance than Increased Trust and Collaboration and Improved Quality Control and Product Authentication. This points out the direct influence blockchain has on improving the customer experience. Through transparency, authenticity of products, and security, blockchain creates trust, hence higher satisfaction and loyalty. Customer confidence is a significant addition to enterprises since satisfied customers tend to buy again and refer the product to other people, which leads to sustained success. Though augmented trust and cooperation, and superior quality control are critical, they are viewed as a result of the technological and economic benefits of blockchain that also include better efficiency in operation and lower cost. Therefore, although these factors help nurture good stakeholder relationships, they are not the primary drivers for the adoption of blockchain in a supply chain.

Improved Risk Management and Compliance: Illustrates the Legal Risk aspect -Reducing the risk and legal rules to be followed. With increased use of blockchain technology, the ability of this technology to enhance compliance and minimize risk in such industries as the automobile sector, which is highly regulated, will become highly critical. The environmental dimension further emphasizes the growing importance of Sustainability and Social Responsibility in global supply chains. Although this is a lower-ranked enabler, it does indicate how blockchain can be used in support of sustainable practices like fair trade and environmental compliance through transparency in the supply chain.

The current analysis points that the adoption of blockchain in the ASC is more technological-based; however, all the dimensions of political, economic, social, legal, and environmental factors equally affect it but are secondary rankings. The integration of methodologies has successfully highlighted the critical enablers and their relative importance across different dimensions by generating important insights into blockchain potential in dealing with problems critical to the automotive supply chain. Such results would have significant implications for practitioners as well as policymakers, as is evidenced by the fact that soon to be initiated efforts to bring in blockchain integration should prioritize technological improvements but at the same time consider regulatory, economic, and social contexts to help in optimizing its benefits.

Therefore, with technological innovations that are ongoing, there is a need to balance innovation drive with strict regulatory adherence that would guarantee blockchain solutions efficiency and acceptance as well as trust among all parties in the supply chain.

With the knowledge acquired from the AHP and TOPSIS analysis, a strong basis for the continuation of the ISM and MICMAC methodologies will be developed. The ISM framework will enable the exploration of interrelations among the primary enablers. It will identify the driving factors that are most critical and those that depend on others.

This analysis will help in making an informed model that portrays all interdependencies and hierarchical relationships about the enablers for more clarity on how they are interlinked and interconnected in order to enhance their impact towards blockchain adoption within the automotive industry. After the TISM methodology, the MICMAC analysis will classify these facilitators based on their influence and dependence. Such phases are required to discover significant empowering factors of blockchain along with the understanding of its influencing nature on other facilitatory factors. By distinguishing into separate groups of the mentioned facilitators: autonomous dependent-linkage and independent variables-MICMAC will provide strategic awareness in better areas that effort focus could be maximized via influence. The above integrated strategy will provide a broad framework for the successful integration of blockchain technology into the automotive supply chain, thus permitting the industry to take benefit of the benefits offered by this revolutionary technology.

4.2 Structuring the Relationship Among Factors: TISM

The Total Interpretive Structural Modeling (TISM) analysis provides a systematic way to understand how different blockchain enablers in the automobile sector are interrelated and influence one another. The enablers are placed into different levels, where the most critical drivers reside at the lower levels, and the outcomes are positioned at higher levels shown in **Figure 4**.

Level 5: ***The Fundamental Drivers***

At the bottom of the hierarchy, **Level 5** represents the most influential enablers, which serve as the foundation for all the other benefits and improvements that blockchain can bring. These enablers have high driving power and are essential prerequisites for higher-level outcomes. The enablers at this level include:

- ***Improved transparency and traceability*****:** Blockchain technology ensures that every transaction and data exchange across the supply chain is transparent and traceable. This enabler is crucial because the entire blockchain system depends on its ability to offer clarity and prevent fraud.
- ***Better efficiency and cost savings*****:** By automating transactions and reducing intermediaries, blockchain can help companies save on operational costs and streamline processes, improving overall efficiency.
- ***Compliance and regulatory requirements*****:** Blockchain can simplify regulatory compliance by providing immutable and transparent records of every step in the production and logistics processes. Meeting regulatory requirements efficiently is a key factor in the automotive industry, which is heavily regulated.

These enablers form the backbone of the blockchain ecosystem. For example, transparency drives trust, which, in turn, enables collaboration and innovation. Similarly, compliance ensures that blockchain systems operate within legal frameworks, further enhancing their adoption. The interconnected nature of these drivers highlights the importance of addressing them comprehensively to unlock blockchain's full potential.

Level 4: ***Intermediate Drivers***

Moving up to **Level 4**, we see enablers that rely on the foundational drivers but also have their own direct impact on higher-level outcomes:

- ***Enhanced security*****:** By the use of the decentralized and cryptographic nature of blockchain, the security is greatly boosted. This is particularly important in the automotive industry, where information on supply chain and transaction data has to be protected against cyber risks and attacks.
- ***Customer satisfaction and loyalty*****:** The customer expects to see what they are buying and blockchain delivers this in a more accountable manner thus enhancing trust. Through proper authentication, safety, and compliance, blockchain increases consumers' satisfaction and their lifetime patronage.

These Level 4 enablers are affected by the Level 5 improvements but also contribute to the development of the outcomes in the subsequent levels.

Level 3: ***Competitive Advantage and Collaboration***

At **Level 3**, the benefits of blockchain become more strategic and competitive:

- ***Innovation and competitive advantage*****:** Businesses that get on the blockchain technology first stand to benefit from the ability to provide better solutions in terms of security, efficiency, and transparency compared to their rivals. This innovation can act as a competitive weapon in the market.
- ***Improved quality control and product authentication*****:** Blockchain makes sure that every action on the supply chain process is recorded, which makes it easier to check the quality and also the authenticity of the products. This is especially important in the automotive industry where there are high risks of using fake parts and low-quality material.
- ***Increased trust and collaboration*****:** Blockchain helps to create a smooth flow of transactions and relations between different participants of the supply chain. Partnership is made more transparent and secure hence partners are willing to collaborate hence making operations to run smoothly and partnership to be stronger.

These **Level 3** enablers are the direct result of improvements in transparency, security, and compliance but contribute significantly to the higher-level goals of sustainability and improved supply chain management.

Level 2: ***Broader Impact***

At **Level 2**, the enabler **Sustainability and social responsibility** emerges. This factor is a broad, macro-level outcome influenced by the combined effect of transparency, efficiency, security, and innovation. Blockchain can help companies demonstrate their commitment to sustainable practices by providing transparent data on sourcing, production, and logistics. For example, blockchain can ensure that raw materials are ethically sourced, leading to more sustainable and socially responsible operations.

Level 1: ***Ultimate Outcome***

At the top of the hierarchy, **Level 1** represents the ultimate outcome that organizations in the automobile sector aim to achieve through blockchain:

- **Improved supply chain management and logistics:** This is the final and most significant benefit that blockchain brings to the automotive industry. By improving transparency, security, efficiency, and collaboration, blockchain leads to a more optimized and responsive supply chain, allowing companies to reduce costs, enhance performance, and meet market demands more effectively.

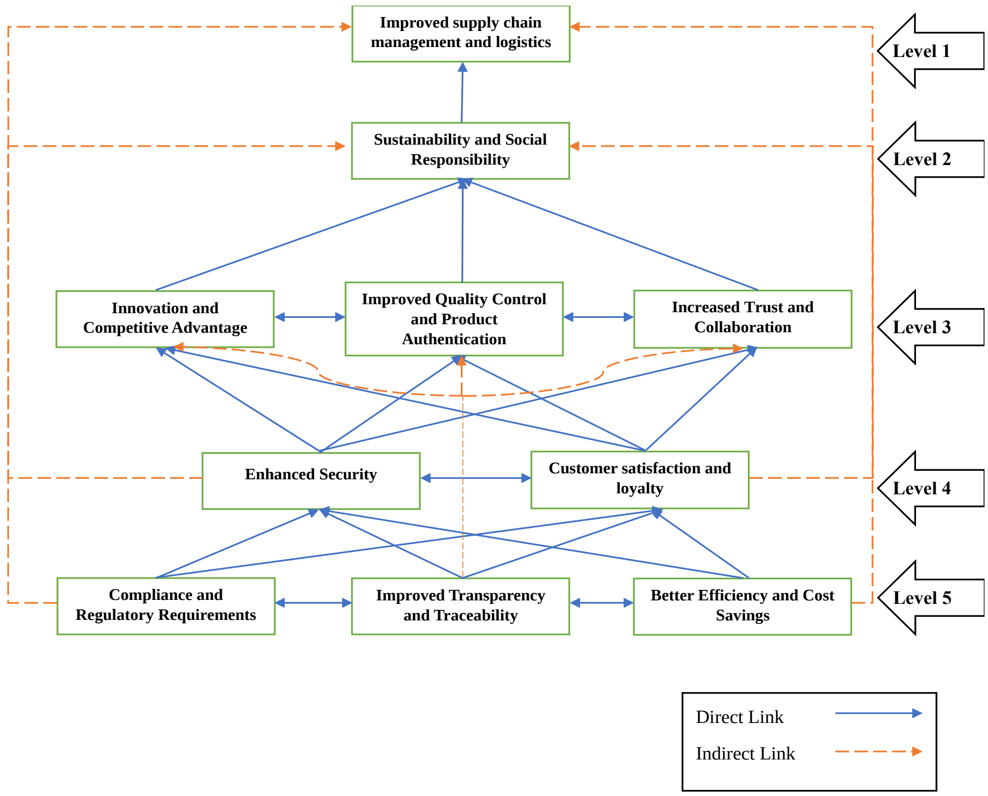

Figure 4. Blockchain enablers TISM modeling.

Figure 4 shows the TISM analysis, which is a holistic hierarchical understanding of the enablers of blockchain technology for the automotive industry. These enablers have been categorized into different tiers; therefore, the TISM model clearly outlines how the primary drivers, such as transparency, efficiency, and compliance, are the pre-requisites to achieve higher-level benefits like sustainability and better supply chain management. This systematic approach underlines the sequential impact of foundational enablers on both intermediate and final results, thereby stressing the importance of targeting essential factors at the foundational level of the hierarchy.

The TISM framework outlines the dynamics of influence while also bringing out the interrelated nature of blockchain enablers. For example, improvement in transparency (Level 5) significantly enhances both trust and collaboration (Level 3), which further enhances sustainable practice (Level 2), and subsequently supply chain management with optimality (Level 1). This interwoven framework depicts the systemic aspect of blockchain implementation, where strategic thinking must be focused on strategic enablers to pursue overall organizational objectives.

Where TISM describes the hierarchical flow, MICMAC classifies these enablers according to their driving and dependence powers, hence giving further insights into how they function within the blockchain ecosystem. It gives a dimension to the dynamic interrelations among enablers in Independent, Linkage, Dependent, and Autonomous variables. Collectively, these analyses should offer a rich, strategically relevant, and holistic framework of understanding regarding the blockchain facilitators in the automotive supply chain.

4.3 Identifying Driving and Dependence Power of Factors: MICMAC

The MICMAC analysis helps to classify blockchain enablers based on their **driving power** (the extent to which an enabler influences others) and dependence power (the extent to which an enabler is influenced by others). This analysis is instrumental in understanding the dynamics between different enablers in the blockchain ecosystem for the automobile sector as shown in **Figure 5**. By dividing the enablers into distinct categories, MICMAC highlights which factors serve as key drivers and which are more reactive or dependent on others.

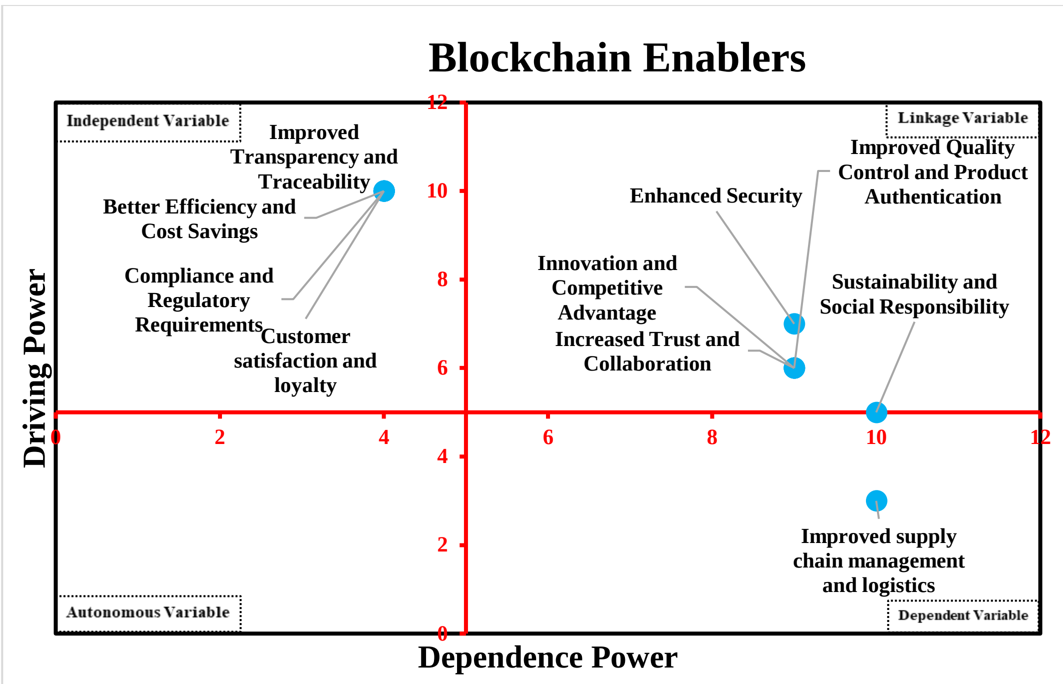

Figure 5. MICMAC Analysis of identified blockchain enablers.

4.3.1 Autonomous Variables (Low Driving Power, Low Dependence Power)

As shown in **Figure 5**, there are no autonomous variables for the automobile sector among blockchain enablers. Autonomous variables have found to have low power of driving and low dependence power. That is to say such variables are mostly isolated and not influential towards or dependent upon other variables to a great extent. Since there are no independent variables, all the enablers here are interlinked and related either to the system or because of it. This depicts that, in this blockchain industry, factors are strongly inter-related such that none of them is separately working or independent of other overall systems.

4.3.2 Dependent Variables (Low Driving Power, High Dependence Power)

Dependent variables are defined by low driving power and high dependence power and denote results that require the support of other enablers. **Figure 5** depicts that "Improved supply chain management and logistics" fits into this category. This enabler also points out that the supply chain improvements are dependent on fundamentals such as increase in transparency, better efficiency and compliance. For instance, transparency helps to track the supply chain in real-time, cost saving and efficiency eliminates operational hitches, which are both essential in managing the logistics chain. This characteristic of the variable is dependent, which underlines its status as the result of a successful blockchain environment. It serves as an indicator of the success of the entire process of implementing blockchain, to indicate whether the primary drivers and linkage variables are doing what is expected of them. It is imperative for companies to put in place the foundational enablers before looking for the enhanced supply chain logistics in blockchain; this shows that in the blockchain ecosystem, the drivers and the outcomes are intertwined.

4.3.3 Linkage Variables (High Driving Power, High Dependence Power)

Linkage variables are characterized by high driving power and high dependence power. These enablers are in the middle of the system because they affect other factors and are affected by them. In this analysis, "Better quality assurance and product identification" and "Environmental conservation and social accountability" are categorized in linkage factors. The blockchain enabled system as depicted in **Figure 5** has its core centered on the aspect of quality control and product authentication. The authenticity of the products and quality control are one of the biggest advantages of using blockchain in the supply chain of the automobile industry because counterfeit spare parts and substandard products are dangerous for lives. However, getting these improvements in quality control is highly dependent with the other enablers including transparency and security. Furthermore, it is also evident that better quality control has a positive effect on other aspects of the business such as the satisfaction of the customers, their trust, and cooperation with other members of the supply chain. Sustainability and social responsibility is another linkage variable. These programs are closely related to the transparency of supply and procurement, as well as to the enhancement of efficiency and compliance with legislation. Blockchain enables sustainability management in supply chains and allows organizations to meet sustainability goals. However, this enabler is also a catalyst for other changes in the supply chain; it affects decisions on sourcing, production processes, and working with sustainable suppliers. This bi-directional relationship with other enablers put sustainability as both as an enabler of blockchain and a receiver of the impact of blockchain. The linkage variables are as dynamic and can either be stabilizing or destabilizing factors depending on how they will be handled. If, therefore, there are no improvements in quality control and sustainability, it may impact the whole ecosystem since they share close linkages with other enablers.

4.3.4 Independent Variables (High Driving Power, Low Dependence Power)

Independent variables have good driving power but low dependence; they are essential agents in the system and are nearly immune to extraneous factors. As depicted in **Figure 5**, the factors labelled as "Enhanced transparency and traceability", "Increased efficiency and cost reduction", and "Compliance and regulation standards" are grouped as independent variables in the current study. Improved transparency and accountability are one of the fundamental premises for the application of blockchain technology in the automotive industry. The fundamental value of blockchain is in its capacity for maintaining clear and immutable records, and its capacity to maintain data credibility within the supply chain. This enabling factor has a significant effect on other results including trust, quality assurance, and security. Transparency builds a basis for additional advantages in that each transaction and data component is transparent and can be traced. It has a strong impact on the performance of other enabling factors but is in turn not much dependent on them. Similarly, more efficiency and cost cutting are the major driving force in the adoption of blockchain technology. Blockchain makes the transactions easier by minimizing the third parties, by automating the business processes and by making it easy to communicate in the supply chain. They produce great revenues and are very crucial in the automotive industry hence the reason why they are called costless efficiencies. This facilitator causes changes, controls supply chain activities and enhances customer satisfaction with minimal dependence on the environment. The last but not the least, the complied regulation is also another independent factor that has a lot of power. This is especially important because blockchain can create verifiable and transparent ledgers that help businesses meet their regulatory obligations. This is one of the factors that drive the adoption of blockchain technology in the automobile industry and particularly in the segment that is most stringent on safety and environmental standards. The accomplishment of this requirement enhances brand confidence and provides companies with opportunities to unlock new opportunities in new foreign markets due to the demonstration of the companies' capacity to meet various regulatory standards. They are the fundamental independent factors that are pushing the adoption of blockchain into the automobile sector. They dictate the general layout and are directly related to the dependent and linkage variables and are therefore the framework for the entire blockchain system.

The MICMAC analysis presented in **Figure 5** provides a dynamic view of the enabling factors of blockchain where driving power and dependence power are considered. It is the independent variables that appear critical to the system and these are things like transparency, efficiency and regulatory compliance just to mention but a few. These first order enablers have a major impact on other factors that determine the adoption of blockchain technology. It is crucial to examine linkage variables, which are characterized by reciprocal effects; they affect numerous results and, at the same time, largely depend on other variables. Largely, dependent variables are the ultimate benefits of the adoption process hence, are the final results of the blockchain system, for instance, enhanced supply chain management. In combination with the MICMAC analysis, the TISM analysis shows the interdependence and the dominance of the enablers of the blockchain. While TISM presents the direction of enablers from the basic enablers to the strategic outcomes, MICMAC on the other hand categorizes the enablers based on the systemic position of the drivers, outcomes and connectors. For instance, the TISM model shows that the system transforms from transparency and security to sustainability and supply chain management, while MICMAC identifies the linkage variables as the key to the system stability. This double view is a good reminder of the fact that blockchain adoption should be done systematically and comprehensively, where the priorities should be identified and where dependencies should be carefully coordinated.

In combination, the analyses provide valuable information for decision makers within the auto industry. Instead, they will have to postulate the need to address independent variables as basic and appropriate for establishing and normalizing linkage variables and the dependent results within which to gauge over-arching success. Thus, by adopting such methodologies, this study offers a round approach to adopt blockchain to the automotive sector which will have a more profound effect of supply chain transparency, efficiency, and resilience. These findings provide the foundation for the creation of possible future intervention plans, which may help explain how blockchain can be applied in a practical manner and reach its full potential.

5. Managerial Implications

The findings of this study are significant for managers and decision-makers in the automotive sector, who are considering the adoption of blockchain technology. The methodologies of AHP-TOPSIS, TISM, and MICMAC provide a strategic framework to rank facilitators that can enhance the process of blockchain adoption and optimize its advantages.

A fundamental implication is the need to focus on compliance and cooperation with regulatory bodies. The prominent role of Compliance and Regulatory Requirements as a critical enabler underscores that automotive companies need to align their blockchain strategies with the evolving legal and regulatory landscapes. For instance, BMW Group has been actively collaborating with regulators and industry associations to ensure that its blockchain initiatives comply with data protection and security regulations. Their blockchain transparency supply chain material source tracking project exemplifies regulatory alignment (Gudymenko et al., 2020). Similarly, companies have to involve the regulators in efforts toward creating rules that will prompt the adoption of blockchain while addressing potential legal issues.

A further important result is the enhancement of chain-to-chain transparency and traceability. The analysis performed through AHP-TOPSIS reveals that transparency and traceability must be improved for visibility to be attained in the supply chain. For example, the Ford Motor Company is using blockchain technology to track the origins of cobalt used in its electric vehicle batteries to ensure that it is sourced ethically and sustainably (Dhondiyal, 2020). This alone ensures traceability but also quality control and minimizes the risk of counterfeit parts. Automotive manufacturers can gain improved transparency and efficiency by establishing unalterable records with blockchain technology in supply chain operations.

Another important aspect of technological integration and security is fostering. better efficiency and cost savings, enhanced security, and improved risk management are some of the operational benefits of blockchain technology adoption. For instance, Daimler AG applied blockchain to make its logistics processes better. Daimler AG has through integration with previous IT infrastructure increased the level of efficiency and minimized the cost while harmonizing operations (Daimler, 2020). The main management involves integration with systems already being used and adequate safe methods which include a smart contract and some cryptographic functions in safeguarding sensitive information as well as automating.

Building internal capabilities and providing training are essential for the successful adoption of blockchain technology. Investing in employee training programs is crucial. For example, Toyota Motor Corporation has developed extensive training initiatives to build expertise in blockchain technology within its workforce (Kim, 2018). These programs cover technical aspects of blockchain as well as regulatory and integration issues, preparing employees to handle future challenges and leverage blockchain's potential effectively.

Other factors include sustainability, and Corporate Social Responsibility (CSR). They descried how Renault Group in partnership with other firms employed blockchain in measuring, evaluation, and monitoring the Sustainable Development Goals indicators such as those relating to emissions and wastes (Renault Group, 2018). The use of blockchain in sustainability processes does not only increases transparency but also gives a competitive advantage because it shows that the company is involved in ethical and sustainability measures. Proper communication of these sustainability efforts to consumers can enhance brand association and therefore build corporate image.

Last but not the least; there is need to incorporate adequate supply chain management and logistic strategies. The TISM analysis reveals that Improved Supply Chain Management and Logistics are influenced by basic enablers such as transparency and compliance with regulations. Volkswagen AG's pilot applications of blockchain, are an example of this approach, which focused on supply chain management. In its use of the blockchain technology, Volkswagen has been able to cut lead times and enhance its inventory control (Xu et al., 2024). Managers should focus on building the fundamental enablers to support a plethora of operational advantages that range from cost efficiencies to enhanced customer satisfaction.

6. Theoretical Implications

This research significantly contributes toward the literature on blockchain technology that integrates AHP-TOPSIS, TISM, and MICMAC methodologies to draw out a nuanced understanding of what enablers blockchain is into the automotive industry. The multimethod approach provides a multi-level framework for evaluating the very critical enablers under the technology adoption process for its adoption. This study encapsulates both the hierarchical rankings and interdependencies among enablers through the amalgamation of quantitative assessments derived from AHP-TOPSIS alongside the structural connections discerned via TISM and MICMAC. Subsequent research endeavors might utilize such an integrative framework in varying sectors or nascent technologies, such as artificial intelligence or quantum computing, so that a deeper insight into the adoption mechanisms of technology can be achieved.

The research also enriches the literature on blockchain in supply chains by providing empirical evidence on the relative importance and interdependencies of blockchain enablers in the automotive industry. It extends previous findings, such as those by Saberi et al. (2018), by emphasizing blockchain's role in improving supply chain performance. Highlighting specific findings that diverge from prior studies can offer new insights into blockchain's impact on supply chain management.

The research shows how adherence to regulations is essential in using blockchain. While earlier studies mention the significance of regulation, this research makes regulatory compliance the central factor that influences all other supporting factors. This finding can be helpful in making a better understanding of how political and legal rules influence the adoption of technology, and it gives areas of future research on how different regulations in various areas impact the spread of technology across different sectors.

Finding linkage variables, such as Improved Quality Control and Product Authentication, helps us understand how blockchain enablers depend on each other. Such variables are important because they influence and are influenced by other factors, showing how complex the adoption process is. Giving examples or case studies that show these interactions helps people understand their role in adopting technology.

This research also contributes to adoption models by focusing on the automotive industry, addressing its unique challenges and needs. By extending generic blockchain adoption models to the automotive sector, this study reflects the industry's emphasis on cost reduction and lean operations. Future research could explore blockchain enablers in other specialized contexts, such as pharmaceuticals or aerospace, to compare sector-specific findings with those from the automotive industry.

Lastly, the step-wise characterization of enablers in the theory of TISM suggests that the introduction of blockchain technology follows sequential stages, where creating a whole-hearted long-term strategy is an essential necessity. This view supports the foundational capability proposition again that, initially, the ability must be put in place for high-order objectives. It can guide the long-term planning to manage the development cycle in case of adopting the blockchain system through foundational capability steps before pursuing the more substantial goals in higher levels.

7. Conclusion and Future Direction

This systematic review of critical enablers in blockchain technology was conducted with a hybrid combination of Analytical Hierarchy Process (AHP), combined Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Total Interpretive Structural Modeling (TISM), and Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC) analysis. Such a hybrid study will result in a rich multiple dependency structure that may help unravel the interdependencies, driving forces, and relative importance of different enablers.

The study ranked the enablers using AHP and TOPSIS in various dimensions. Political dimension ranked compliance and regulatory requirements at sixth, indicating the pivotal role they play in instilling trust and legitimacy. Improved supply chain management and logistics rank at tenth while increased automation and operational efficiency ranked eleventh, both moderate influencers. Socially, increased trust and cooperation and better-quality control and product assurance ranked in fourth and fifth places respectively but underscored their importance in receiving broader acceptance. Technical, greater transparency and traceability, security, efficient effectiveness, and cost savings were ranked at first place, second place, third place, respectively; these all noted their critical importance. Better risk control and compliance ranked in twelfth place in the list and by environmental standards, sustainability ranked seventh place.

From the TISM modeling, it was evident that enhanced security serves as a foundational element that influences a range of other enablers such as compliance and regulatory requirements, innovation, competitive advantage, and improved supply chain management and logistics. The hierarchical structure highlighted that enhanced security underpins many of the higher-level benefits of blockchain, including customer satisfaction, better efficiency, and increased automation.

Further to MICMAC analysis, it revealed that the characteristics of blockchain enablers are more about linkage. The linkage variables are: enhanced security, innovation and competitive advantage, better risk management and compliance, and increased automation and operational efficiency. All linkage variables have very high driving and dependence power. Improved transparency and traceability-classified as a dependent variable of the study-had crucial importance in driving those such as better efficiency, cost saving, and better satisfaction of regulatory requirements.

Literature and practice are improved within this study by contributing towards an integrative framework that aggregates results from multi-method analyses so to assess the relative importance and interdependence of blockchain enablers. The findings are actionable for managers in terms of prioritizing regulatory compliance, enhancing supply chain transparency, and fostering technological integration for successful blockchain adoption. Future research should investigate sector-specific variations and the changing regulatory landscape to further hone these insights.

Building on the findings of this study, future research should focus on several key areas to further advance the understanding and implementation of blockchain technology:

- Security Protocols: Being a foundation, further research in the area should be oriented toward developing stronger security protocols that can ward off emerging cyber threats. This will involve advanced encryption techniques, secure key management, and more robust consensus mechanisms.
- Regulatory Frameworks: More research is needed on regulatory frameworks to create flexible yet robust structures that can adapt well to fast-paced evolution of blockchain technology: International cooperation towards the standardization of regulations as well as compliance with borders.
- Integration with Existing Systems: The research point should be integrating into the existing IT infrastructures to be more efficient and cost-effective. In this case, interoperable standards and protocols should be developed.

By addressing these areas, future research can help to fully realize the potential of blockchain technology, driving its adoption and maximizing its benefits across different sectors.

Conflict of Interest

The authors declare that there is no conflict for this publication.

AI Disclosure

The author(s) declare that no assistance is taken from generative AI to write this article.

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Annexure 1- Detailed steps of MCDM methods.

Section A. Decision matrix.

Table A1. Normalized decision matrix for blockchain enablers.

Factors→ / Experts↓	Improved transparency and traceability, E1	Enhanced security, E2	Better efficiency and cost Savings, E3	Increased trust and collaboration. E4	Improved quality control and product authentication, E5	Compliance and regulatory requirements, E6	Sustainability and social responsibility, E7	Innovation and competitive advantage, E8	Customer satisfaction and loyalty, E9	Improved supply chain management and logistics, E10	Increased automation and operational efficiency, E11	Better risk management and compliance, E12
E1	0.2667	0.2957	0.2100	0.2236	0.3032	0.2132	0.3114	0.2274	0.3227	0.4003	0.2357	0.2402
E2	0.3333	0.2957	0.3501	0.0745	0.0758	0.2843	0.0778	0.1516	0.1291	0.0801	0.2357	0.2402
E3	0.2000	0.2957	0.2100	0.2981	0.3032	0.2843	0.2335	0.3032	0.3227	0.2402	0.3143	0.3203
E4	0.2667	0.2218	0.2801	0.3727	0.3032	0.2843	0.3892	0.3790	0.3227	0.3203	0.3143	0.2402
E5	0.2000	0.1478	0.2100	0.2236	0.2274	0.2132	0.1557	0.1516	0.0645	0.0801	0.1571	0.2402
E6	0.2000	0.1478	0.2100	0.2236	0.2274	0.2132	0.1557	0.1516	0.0645	0.0801	0.1571	0.2402
E7	0.2000	0.2957	0.2100	0.2981	0.3032	0.2843	0.2335	0.3032	0.3227	0.2402	0.3143	0.3203
E8	0.2667	0.2218	0.2801	0.3727	0.3032	0.2843	0.3892	0.3790	0.3227	0.3203	0.3143	0.2402
E9	0.2667	0.2957	0.2100	0.2236	0.3032	0.2132	0.3114	0.2274	0.3227	0.4003	0.2357	0.2402
E10	0.3333	0.2957	0.3501	0.0745	0.0758	0.2843	0.0778	0.1516	0.1291	0.0801	0.2357	0.2402
E11	0.2000	0.1478	0.2100	0.2236	0.2274	0.2132	0.1557	0.1516	0.0645	0.0801	0.1571	0.2402
E12	0.2000	0.2957	0.2100	0.2981	0.3032	0.2843	0.2335	0.3032	0.3227	0.2402	0.3143	0.3203
E13	0.2667	0.2218	0.2801	0.3727	0.3032	0.2843	0.3892	0.3790	0.3227	0.3203	0.3143	0.2402
E14	0.2667	0.2957	0.2100	0.2236	0.3032	0.2132	0.3114	0.2274	0.3227	0.4003	0.2357	0.2402
E15	0.3333	0.2957	0.3501	0.0745	0.0758	0.2843	0.0778	0.1516	0.1291	0.0801	0.2357	0.2402

Section B. AHP calculations.

Table B1. Geometric mean (GM) and normalized GM (weight) calculations for blockchain enablers.

Blockchain enablers	**Geometric mean**	**Normalized geometric means (weight)**
Improved transparency and traceability	0.818794	0.067607
Enhanced security	0.928485	0.076665
Better efficiency and cost savings	0.867286	0.071611
Increased trust and collaboration	1.080405	0.089209
Improved quality control and product authentication	1.066549	0.088065
Compliance and regulatory requirements	0.856164	0.070693
Sustainability and social responsibility	1.171669	0.096744
Innovation and competitive advantage	1.019997	0.084221
Customer satisfaction and loyalty	1.011703	0.083536
Improved supply chain management and logistics	1.345894	0.11113
Increased automation and operational efficiency	0.983474	0.081205
Better risk management and compliance	0.960577	0.079314
Availability of blockchain skill set	0.919622	0.065126

Section C. TOPSIS calculations.

Using TOPSIS, solution alternatives are controlled from a finite set using a multi-criteria decision-making procedure that maximizes distance from the negative ideal point while minimizing the distance from the positive ideal point. The steps are as follows:

Step 1: Determine the weighted normalized decision matrix.
The weighted normalized decision matrix is calculated by multiplying the weight of each criterion calculated using AHP by the above matrix

Table C1. Weighted normalized decision matrix (blockchain enablers).

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Weights calculated Using AHP	0.0676	0.0767	0.0716	0.0892	0.0881	0.0707	0.0967	0.0842	0.0835	0.1111	0.0812	0.0793
Weighted Normalized Decision Matrix	0.0180	0.0227	0.0150	0.0199	0.0267	0.0151	0.0301	0.0192	0.0270	0.0445	0.0191	0.0191
	0.0225	0.0227	0.0251	0.0066	0.0067	0.0201	0.0075	0.0128	0.0108	0.0089	0.0191	0.0191
	0.0135	0.0227	0.0150	0.0266	0.0267	0.0201	0.0226	0.0255	0.0270	0.0267	0.0255	0.0254
	0.0180	0.0170	0.0201	0.0332	0.0267	0.0201	0.0377	0.0319	0.0270	0.0356	0.0255	0.0191
	0.0135	0.0113	0.0150	0.0199	0.0200	0.0151	0.0151	0.0128	0.0054	0.0089	0.0128	0.0191
	0.0135	0.0113	0.0150	0.0199	0.0200	0.0151	0.0151	0.0128	0.0054	0.0089	0.0128	0.0191
	0.0135	0.0227	0.0150	0.0266	0.0267	0.0201	0.0226	0.0255	0.0270	0.0267	0.0255	0.0254
	0.0180	0.0170	0.0201	0.0332	0.0267	0.0201	0.0377	0.0319	0.0270	0.0356	0.0255	0.0191
	0.0180	0.0227	0.0150	0.0199	0.0267	0.0151	0.0301	0.0192	0.0270	0.0445	0.0191	0.0191
	0.0225	0.0227	0.0251	0.0066	0.0067	0.0201	0.0075	0.0128	0.0108	0.0089	0.0191	0.0191
	0.0135	0.0113	0.0150	0.0199	0.0200	0.0151	0.0151	0.0128	0.0054	0.0089	0.0128	0.0191
	0.0135	0.0227	0.0150	0.0266	0.0267	0.0201	0.0226	0.0255	0.0270	0.0267	0.0255	0.0254
	0.0180	0.0170	0.0201	0.0332	0.0267	0.0201	0.0377	0.0319	0.0270	0.0356	0.0255	0.0191
	0.0180	0.0227	0.0150	0.0199	0.0267	0.0151	0.0301	0.0192	0.0270	0.0445	0.0191	0.0191
	0.0225	0.0227	0.0251	0.0066	0.0067	0.0201	0.0075	0.0128	0.0108	0.0089	0.0191	0.0191

Step 2: Determine the ideal and negative-ideal solutions

Next, the ideal and negative-ideal solutions are determined as follows:
Ideal solution: For each criterion, find the maximum value among all alternatives (i.e., the best performance on that criterion).

Negative-ideal solution: For each criterion, find the minimum value among all alternatives (i.e., the worst performance on that criterion).

Table C2. Ideal and negative-ideal solution (blockchain enablers).

Enabler	Ideal solution	Negative-ideal solution
Improved Transparency and Traceability	0.023	0.014
Enhanced Security	0.023	0.011
Better Efficiency and Cost Savings	0.025	0.015
Increased Trust and Collaboration	0.033	0.007
Improved Quality Control and Product Authentication	0.027	0.007
Compliance and Regulatory Requirements	0.020	0.015
Sustainability and Social Responsibility	0.038	0.008
Innovation and Competitive Advantage	0.032	0.013
Customer satisfaction and loyalty	0.027	0.005
Improved supply chain management and logistics	0.044	0.009
Increased automation and operational efficiency	0.026	0.013
Better risk management and compliance	0.025	0.019

Finally, the distance of each alternative to the ideal and negative-ideal solutions is calculated using the Euclidean distance formula:

$Si+ = \sqrt{(\sum (Vij - Ij)^2)}$

$Si- = \sqrt{(\sum (Vij - Nj)^2)}$

The final step is to calculate the relative closeness to the ideal solution for each alternative:
$Ci = Si- / (Si+ + Si-)$

The alternative with the highest Ci value is considered the best option.
The following table describes the distance from the ideal and non-ideal solutions.

Table C3. Distance from ideal and negative-ideal solution and relative closeness to the ideal solution (blockchain enablers).

Enabler	Distance from ideal solution	Distance from negative-ideal solution	Relative closeness to the ideal solution
Improved transparency and traceability	0.047	0.028	0.370
Enhanced security	0.042	0.034	0.450
Better efficiency and cost savings	0.043	0.030	0.412
Increased trust and collaboration	0.044	0.047	0.516
Improved quality control and product authentication	0.044	0.045	0.506
Compliance and regulatory requirements	0.042	0.028	0.403
Sustainability and social responsibility	0.047	0.053	0.531
Innovation and competitive advantage	0.042	0.042	0.502
Customer satisfaction and loyalty	0.051	0.045	0.469
Improved supply chain management and logistics	0.056	0.067	0.545
Increased automation and operational efficiency	0.037	0.038	0.503
Better risk management and compliance	0.037	0.035	0.490

Section D. The steps of ISM are as follows.

Structural Self-Interaction Matrix (SSIM).

SSIM is developed based on the contextual relationship established between barriers represented as i and j. According to Sage (1977), the relationship between any two variables, in our case barriers, can be represented by four standard symbols (V, X, A, O), which would help in giving a direction to the flow of the relationship. This representation is depicted in **Table D1**.

Table D1. Conversion algorithms for SSIM to initial reachability matrix.

Representative symbols	i → j	j → i	(i,j) th entry	(j,i) th entry
V	✓	×	1	0
A	×	✓	0	1
X	✓	✓	1	1
O	×	×	0	0

Once SSIM is developed, it should be further discussed with opinion experts so that the result of SSIM is validated. **Table D2** depict the SSIM of the enablers of Blockchain implementation in automobile sector.

Table D2. Structural self-interaction matrix (SSIM) (enablers of blockchain).

Variables	1	2	3	4	5	6	7	8	9	10
Improved transparency and traceability	-	V	X	V	V	X	V	V	X	V
Enhanced security		-	A	X	X	A	V	X	A	V
Better efficiency and cost savings			-	V	V	X	V	V	X	V
Increased trust and collaboration				-	X	A	X	X	A	V
Improved quality control and product authentication					-	A	X	X	A	V
Compliance and regulatory requirements						-	V	V	X	V
Sustainability and social responsibility							-	X	A	X
Innovation and competitive advantage								-	A	V
Customer satisfaction and loyalty									-	V
Improved supply chain management and logistics										-

The initial reachability matrix (SSIM representation using 1s and 0s instead of V, A, X, and O) is constructed by substituting barriers. **Table D3** shows this matrix, while **Table D4** presents the final reachability matrix, highlighting driving power and dependency of blockchain enablers. The final matrix is derived through transitivity analysis, where if A relates to B and B relates to C, then A also relates to C. This iterative process refines the reachability matrix to establish interdependencies.

Level partitioning follows the final reachability set formation, where Reachability, Antecedent, and Intersection Sets are generated. Enablers with common reachability sets are iteratively removed to establish their priority in the ISM methodology. This process continues until all factors are assigned to their respective levels in the ISM model, forming the directed graph. **Table D5** lists the level partitioning (LP) to Blockchain adoption in the automotive industry, while **Table D6** presents the final reduced conical matrix used to construct the ISM model**.**

Table D3. Initial reachability matrix (blockchain enablers).

Variables	1	2	3	4	5	6	7	8	9	10	Driving power
Improved transparency and traceability	1	1	1	1	1	1	1	1	1	1	12
Enhanced security	0	1	0	1	1	0	1	1	0	1	8
Better efficiency and cost savings	1	1	1	1	1	1	1	1	1	1	12
Increased trust and collaboration	0	1	0	1	1	0	1	1	0	1	8
Improved quality control and product authentication	0	1	0	1	1	0	1	1	0	1	8
Compliance and regulatory requirements	1	1	1	1	1	1	1	1	1	1	12
Sustainability and social responsibility	0	0	0	1	1	0	1	1	0	1	7
Innovation and competitive advantage	0	1	0	1	1	0	1	1	0	1	8
Customer satisfaction and loyalty	1	1	1	1	1	1	1	1	1	1	12
Improved supply chain management and logistics	0	0	0	0	0	0	1	0	0	1	2
Dependence power	4	10	4	11	11	4	12	11	4	12	

Table D4. Final reachability matrix (blockchain enablers).

Variables	1	2	3	4	5	6	7	8	9	10	Driving power
Improved transparency and traceability	1	1	1	1	1	1	1	1	1	1	10
Enhanced security	0	1	0	1	1	0	1	1	0	1	7
Better efficiency and cost savings	1	1	1	1	1	1	1	1	1	1	10
Increased trust and collaboration	0	1	0	1	1	0	1	1	0	1	6
Improved quality control and product authentication	0	1	0	1	1	0	1	1	0	1	6
Compliance and regulatory requirements	1	1	1	1	1	1	1	1	1	1	10
Sustainability and social responsibility	0	0	0	1	1	0	1	1	0	1	5
Innovation and competitive advantage	0	1	0	1	1	0	1	1	0	1	6
Customer satisfaction and loyalty	1	1	1	1	1	1	1	1	1	1	10
Improved supply chain management and logistics	0	1*	0	0	0	0	1	0	0	1	3
Dependence power	4	9	4	9	9	4	10	9	4	10	

Table D5. Level partitioning (LP) blockchain enablers.

Elements (Mi)	Reachability set R(Mi)	Antecedent set A(Ni)	Intersection set R(Mi)∩A(Ni)
1	1, 3, 6, 9,	1, 3, 6, 9,	1, 3, 6, 9,
2	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,
3	1, 3, 6, 9,	1, 3, 6, 9,	1, 3, 6, 9,
4	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,
5	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,
6	1, 3, 6, 9,	1, 3, 6, 9,	1, 3, 6, 9,
7	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,
8	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,
9	1, 3, 6, 9,	1, 3, 6, 9,	1, 3, 6, 9,
10	2, 4, 5, 7, 8, 10, 11, 12,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,	2, 4, 5, 7, 8, 10, 11, 12,

Table D6. Reduced conical matrix (CM) blockchain enablers.

Variables	Dependence power	Driving power	Level
Improved transparency and traceability	4	10	5
Better efficiency and cost savings	9	10	5
Compliance and regulatory requirements	4	10	5
Customer satisfaction and loyalty	9	10	4
Enhanced security	9	7	4
Increased trust and collaboration	4	6	3
Improved quality control and product authentication	10	6	3
Innovation and competitive advantage	9	6	3
Sustainability and social responsibility	4	5	2
Improved supply chain management and logistics	10	3	1

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