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Designing a Blockchain Technology Model in the Sustainable Supply Chain Finance of the Automotive Parts Manufacturing Industry (Quantitative and Qualitative Approach)

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A B S T R A C T

This study developed a blockchain technology model for sustainable supply chain finance in the automotive parts manufacturing industry, using a mixed-methods approach. The qualitative phase, involving 10 experts, utilized grounded theory to identify causal, contextual, and intervening factors. The quantitative phase involved 11 experts for initial model design and 214 managers for evaluation. Fuzzy Delphi analysis identified 13 key components for the financial sustainability of automotive parts supply chains. Interpretive Structural Modeling (ISM) revealed independent dimensions like technology, infrastructure, standardization, policymaking, and legal/regulatory frameworks. Dependent dimensions included financial system development, sustainable goals, and supply chain integration. Interconnected dimensions were financial flexibility, a centralized (blockchain-centric) business model, and blockchain information management. The designed model was tested using Structural Equation Modeling (SEM), demonstrating strong fit and performance. SEM confirmed positive relationships among the legal/regulatory framework, standardization, blockchain information management, and the centralized business model. Organizational policymaking positively influenced technology, infrastructure, and blockchain information management. Furthermore, the centralized business model significantly impacted supply chain integration and sustainable financial flexibility. The study concludes that novel blockchain-centric business models, robust integration, and financial flexibility are crucial within sustainable supply chains for enhancing financial performance, mitigating risks, and achieving broader sustainability objectives.

Keywords: *Sustainable Supply Chain Finance (SSCF); Blockchain Technology (BT); Interpretive-structural modeling (ISM); Structural Equations Modeling (SEM); Quantitative and Qualitative Approach*

1. Introduction

The global economic landscape is characterized by increasingly fragmented, complex, and dynamic supply chains, facing unprecedented pressures from globalization, technological advancements, and a growing emphasis on sustainability. Modern supply chains are not merely logistical networks but intricate ecosystems of interconnected entities, financial flows, and information exchanges, often spanning multiple continents and diverse regulatory environments (Irawan, 2023; Mangan & Lalwani, 2016). Within this complexity, industries like automotive parts manufacturing, with their multi-tiered structures, extensive supplier networks, and stringent quality demands, represent a critical domain where efficiency, transparency, and financial stability are paramount (Masoumi et al., 2019).

However, these very characteristics that drive global efficiency also present significant vulnerabilities. Issues such as lack of end-to-end visibility, information asymmetry, financial bottlenecks, and exposure to environmental, social, and governance (ESG) risks have become prevalent (Guo et al., 2024; Martiny et al., 2024). The growing awareness of climate change, ethical sourcing, and social responsibility has consequently amplified the need for sustainable practices across the entire supply chain, moving beyond mere compliance to becoming a strategic imperative for long-term resilience and competitiveness (Muhammad Shujaat et al., 2025).

The Automotive Parts Manufacturing Industry (APMI) stands as a basis of the global economy, characterized by its highly specialized components, just-in-time (JIT) delivery systems, and a complex web of original equipment manufacturers (OEMs) and thousands of suppliers of varying sizes and capabilities (Dakić et al., 2024). This industry faces unique sustainability challenges, including significant energy consumption, waste generation, raw material sourcing ethics, and environmental impact throughout the product lifecycle (Wellbrock et al., 2020). Financially, the APMI is often plagued by extended payment terms, high transaction costs, and limited access to affordable capital for smaller, often more sustainable, suppliers (Slavinskaitė et al., 2025). This financial strain can hinder investments in sustainable technologies and practices, creating a vicious cycle where sustainability initiatives are postponed due to financial constraints. The inherent complexity and opacity of the current financial mechanisms within this industry thus pose a significant barrier to achieving holistic supply chain sustainability (Rashid et al., 2019).

In response to these interconnected challenges, Sustainable Supply Chain Finance (SSCF) has emerged as a critical paradigm. SSCF integrates environmental, social, and governance (ESG) criteria into financial decisions and mechanisms across the supply chain, aiming to incentivize sustainable behavior by offering attractive financing options to suppliers who demonstrate improved sustainability performance (Parung, 2019; Safaei Ghadikalai & Vedadi, 2015). By linking financial benefits (e.g., lower interest rates, faster payments) to sustainability metrics, SSCF seeks to create a win-win scenario, benefiting both the financial health of suppliers and the overall sustainability performance of the entire value chain (Choi, 2020).

Early research on SSCF conceptualized its role in bridging the gap between sustainability reporting and financial performance (Tseng et al., 2019). Key drivers for SSCF adoption include enhanced reputation, risk mitigation, improved supplier relationships, and increased supply chain resilience (Hofmann & Sertori, 2020; Jia et al., 2020). However, the implementation of effective SSCF programs is often hampered by a lack of verifiable and real-time data on supplier sustainability performance, trust issues among supply chain partners, and the high administrative costs associated with traditional financing instruments (Tseng et al., 2019; Zhou & Masi, 2025). These limitations underscore the need for innovative technological solutions to unlock the full potential of SSCF.

Supply chain management (SCM) has become a cornerstone of organizational competitiveness, emphasizing efficiency, risk resilience, and sustainability. Operational optimization through metaheuristic algorithms, such as Particle Swarm Optimization (PSO), significantly improves vehicle routing, reduces delivery times, and enhances service quality in distribution systems (Saadi, 2023). At the same time, the complexity of supply chain networks requires robust risk management frameworks. The Risk Efficiency Index (REI), combined with fuzzy-based methods, provides a systematic approach to identify, evaluate, and prioritize risks while optimizing resource allocation for mitigation (Hajigol Yazdi & Fakhrzad, 2020). Furthermore, environmental sustainability is increasingly critical, as demonstrated in the automotive industry, where integrating environmental performance indicators into supply chain evaluation fosters both competitive advantage and sustainable development (Tawfeeq Saleh Al-Sammarraie & Fathi, 2025). Collectively, these perspectives highlight the necessity of adopting integrated approaches that balance efficiency, resilience, and sustainability to achieve effective SCM.

Blockchain technology (BT), a distributed, immutable, and cryptographically secure ledger, has rapidly gained traction across various industries due to its potential to enhance transparency, traceability, and trust within complex networks (Agarwal et al., 2022; Duan et al., 2023). Its core features—decentralization, immutability, consensus mechanisms, and smart contracts—offer a promising solution to many of the systemic inefficiencies inherent in traditional supply chains and their financing mechanisms (Alazab et al., 2021; Aslam et al., 2021). By providing a shared, tamper-proof record of transactions and events, blockchain can mitigate information asymmetry, reduce fraud, and streamline complex multi-party processes.

Recent research highlights the diverse applications and challenges of blockchain adoption in supply chains, particularly concerning sustainability and finance. BT is shown to enable new, collaboration-centric business models for mobile operators in developing countries (Queiroz et al., 2021) and significantly enhance sustainable SCM through features like data transparency, traceability, quality assurance, and smart contracts (Fathi & Sadeghi, 2021). It also positively impacts operational performance (Aslam et al., 2021) and customer satisfaction in manufacturing SCM, highlighting customer trust and green processes as key improvement areas (Hong & Hales, 2021). Key factors driving BT adoption include technological readiness, organizational willingness, general facilitating conditions, and the moderating role of regulatory support (Alazab et al., 2021). Behavioral acceptance is influenced by facilitating conditions, trust, social influence, and effort expectation (Queiroz et al., 2021), as well as information system success and task-fit with technology, with inter-organizational trust being crucial (Alazab et al., 2021). However, implementation faces significant barriers such as the inadequacy of traditional business models, high capital costs, data security concerns, limited tool availability, and complex integration, particularly in health and logistics sectors (Öztürk & Yildizbaşi, 2020). These studies often employ diverse methodologies, including qualitative content analysis, multi-criteria decision-making, fuzzy modeling, and structural equation modeling. Kumar (Kumar & Kumar Barua, 2023) identified key barriers to blockchain implementation in the oil supply chain as a lack of comprehensive standards, distrust among partners, and insufficient technological understanding. Similarly, Kumar Singh (Kumar Singh et al., 2023) found significant obstacles in sustainable construction projects, including poor blockchain-based policy implementation, low awareness, customer resistance, technological immaturity, market uncertainty, and access issues. Cao (Cao et al., 2023) proposed a blockchain-based framework to enhance food supply chain sustainability through reliable communication of product features. Guo (Guo et al., 2024) showed that blockchain adoption positively impacts sustainable supply chain finance, with supply and demand transparency acting as partial mediators, although ethical leadership can weaken its effect on demand transparency. For small and medium-sized enterprises (SMEs), Asante Boakye (Asante Boakye et al., 2025) found that relative advantage, compatibility, trialability, regulatory support, and market dynamism positively influence blockchain adoption in Ghana, while complexity and cost have a negative impact.

Despite the individual advancements in understanding SSCF and the capabilities of blockchain technology, a significant research gap persists concerning the comprehensive integration of blockchain specifically to facilitate sustainable supply chain finance within the automotive parts manufacturing industry. While conceptual frameworks exist for blockchain in supply chains (Choi, 2020) and the theoretical benefits of SSCF are acknowledged, there is a paucity of research that rigorously designs and validates a practical blockchain-based model tailored to the unique financial and sustainability challenges of APMI. Therefore, the findings from this research can open up new frontiers of discussion for both academics and professionals, for example, addressing topics such as reducing opportunistic behavior among supply chain members, regulatory support for smart contracts, blockchain social responsibility, and more. This study guides managers and decision-makers in automotive parts manufacturing to evaluate their current supply chain practices, understand the relationship between supply chain practices and BT features, and recognize how various blockchain features can contribute to improving supply chain practices and, ultimately, enhancing operational performance. Hence, the main objective of this research is to design and develop a BT model within a SSCF.

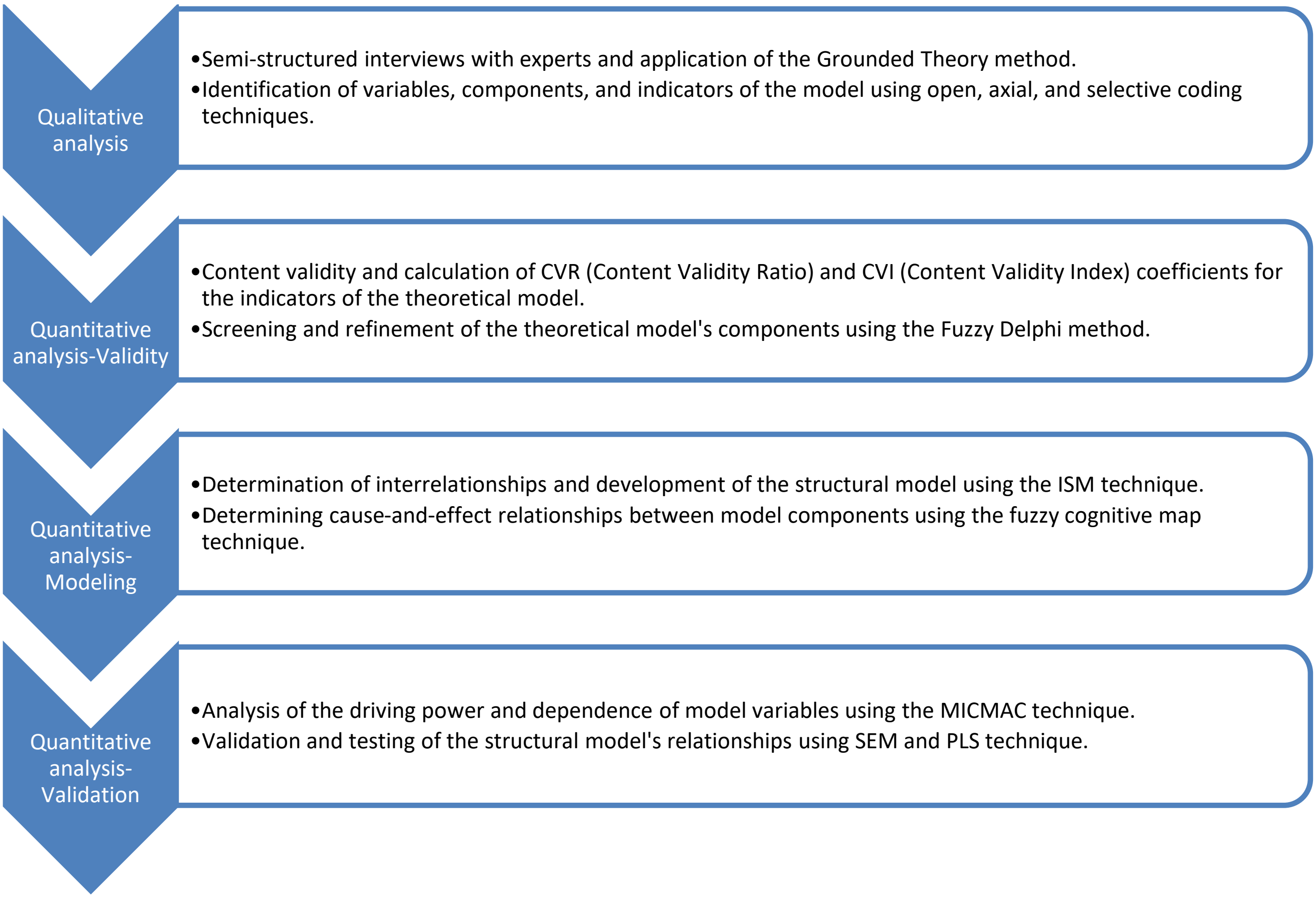
2. Methods and Materials

This research explores the nature of phenomena, relationships between variables, principles, and the development of new theories and models within Blockchain

Technology (BT) in supply chain, with a specific emphasis on finance. By expanding the boundaries of knowledge in this scientific field, its overarching purpose is applied-developmental. This study employed a mixed-methods approach, combining both qualitative and quantitative methodologies, and was cross-sectional in terms of data collection time. An overview of the research implementation process is depicted in Figure 1.

Figure 1

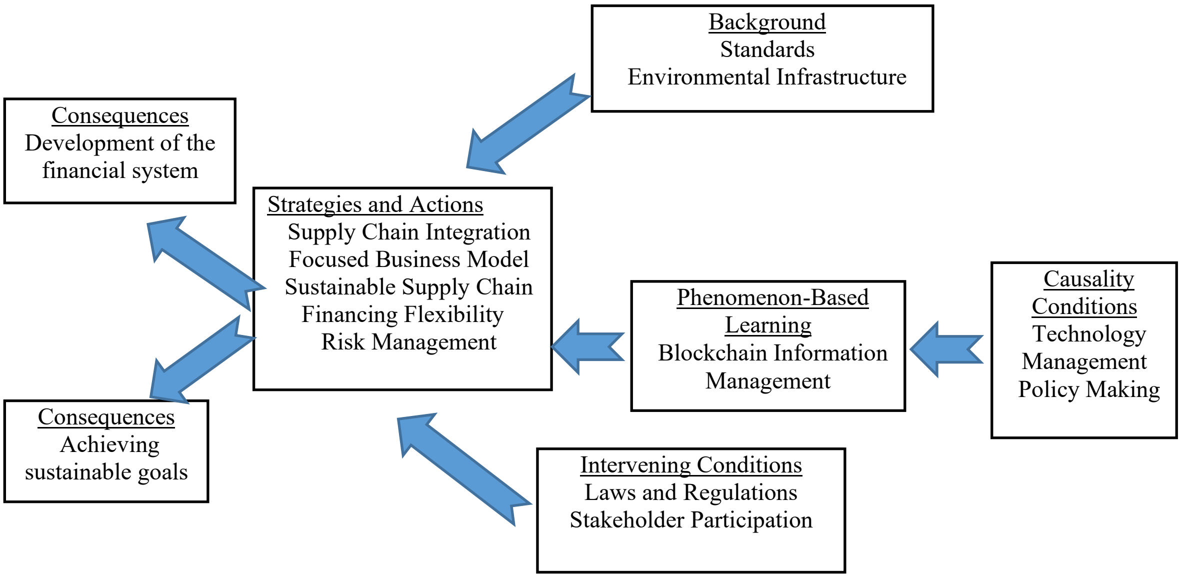
Research Process Flowchart



The qualitative phase utilized a Grounded Theory approach, specifically drawing on the Strauss and Corbin methodology for axial coding. This paradigm provides a robust framework for evaluating relationships between categories, enabling a comprehensive understanding of the studied phenomenon by systematically identifying: causal and contextual conditions, the core phenomenon, strategies adopted, intervening conditions, and resulting consequences. Figure 2 shows the paradigmatic model of BT within a SSCF. Semi-structured interviews were conducted with experts using the Grounded Theory technique. Through an inductive approach and data coding techniques, variables and components were identified, leading to the presentation of a preliminary theoretical model. To further refine these initial qualitative outputs and prioritize key elements, the fuzzy Delphi method was applied using qualitatively designed questionnaires based on a 5-option scale (Table 1).

Figure 2

Paradigmatic model of BT within a SSCF



The quantitative phase was designed to be both causal and correlational. This study did not begin with pre-defined hypotheses. Instead, the relationships between the identified variables and the conceptual model were developed through the Interpretive Structural Modeling (ISM) technique, based on expert opinions. Subsequently, the causal relationships among the model's components were determined using the fuzzy cognitive mapping method, which justifies the adoption of a causal research approach. Following model construction, a questionnaire incorporating pairwise comparisons and a 5-point Likert scale, informed by the fuzzy Delphi results, was used for the ISM analysis. Finally, the designed model was validated within the broader statistical population using Structural Equation Modeling (SEM) with the Partial Least Squares (PLS) technique, reflecting the correlational aspect of the research.

The study involved two distinct research populations corresponding to the qualitative and quantitative phases. In qualitative phase (Grounded Theory Interviews), the target population comprised senior managers from Iran's 10 largest automobile parts manufacturing companies (as ranked by the Ministry of Industry, Mine, and Trade). Non-probability purposive and theoretical sampling methods were employed. Theoretical saturation served as the primary criterion for determining sample size, with iterative sampling continuing until data saturation was reached, enabling theoretical abstraction. Ten experts were purposefully interviewed until saturation was achieved, with each possessing a minimum of 15 years of management experience and holding at least a Master's degree. The quantitative phase was divided into two stages:

- Model Generation (ISM/Fuzzy Cognitive Mapping): For this stage, which necessitated expert opinions for the ISM approach, the initial 10 interviewed experts were supplemented by an additional 11 experts (comprising financial and IT managers). These 11 experts were recruited through non-probability, purposive, and snowball sampling from the same top 10 automotive parts manufacturing companies, totaling 21 experts for model construction.
- Model Validation (SEM-PLS): The statistical population for validation encompassed 150 automotive parts manufacturing companies nationwide. From this, a sampled population of 483 relevant managers (including senior, financial, IT, and supply chain managers) was identified. Using Cochran's formula for probability sampling, 214 individuals were selected. Accounting for an anticipated 10% questionnaire non-response rate, a total of 235 questionnaires were electronically distributed. Ultimately, 234 complete responses were received and prepared for data analysis.

Table 1

Dimensions, components, and indicators of the BT Model within SSCF for Automotive Parts Manufacturers

Selective Coding	Axial Coding	Open Coding
Intervening Conditions	Laws and Regulations	New laws and regulations for the promotion and adoption of BT
		Legal status of blockchain records
		Intellectual property issues
		Support and cooperation with regulatory bodies
		Government-led initiatives
		Licensing and compliance
		Governance frameworks
		Development of ethical guidelines
	Stakeholder Participation	Incentive mechanisms for stakeholder participation in blockchain
		User adoption
		User understanding of resources and availability of support for participation
Background conditions	Standards	Standardization as a prerequisite for blockchain adoption in SCF
		Harmonization of accounting standards by multiple stakeholders
		Data protection regulations
		Clear legal status for digitized ownership documents
		Legal enforceability of smart contracts
		Alignment between blockchain state and legal status
	Infrastructure	Availability of renewable energies
		Size and bandwidth
		Background and smart technologies for Industry 4.0
Causality conditions	Technology Management	Technological maturity
		Technological competence
		Operational throughput
		Hardware/software availability
		Blockchain-based SC financing platform
		Technical expertise
	Policy Making	Appropriate organizational structure
		Financial and investment support
		Technological knowledge management
		Sustainable supply chain strategies alignment with blockchain financing
		Collaboration and coordination capabilities in business processes
		Comprehensive training programs and skilled staff
		Ethical and environmental responsibilities
		Flexibility in planning
		Creating shared benefits in blockchain-based sustainable supply chain financing
Phenomenon-Based Learning	Blockchain information management	Adequacy of Data and Information Reliability
		Smart contracts
		Data privacy and security
		Scalability
		System integration capabilities
		Financial information asymmetry
		Availability of technical support
		Information sharing
Strategies	Supply chain integration	Collaboration and coordination capabilities in financial business processes and supply chains
		Competition strategy
		Integration of financing processes
		Trust and transparency in the supply chain
		Planning for integrating your supply chain's financial services sector into a blockchain environment
		Information sharing

		Cultural engagement for adopting innovations
		Authenticity and integrity throughout the supply chain
		Facilitating the development of supply chains and financial activities
		Ability to flexibly develop and deploy blockchain and other digital technologies
		Deconstructing supply chain operations and financial activities
		Finding business partners and trade-related documents
	Centralized business model	Green business processes for financing
		Redesigned operational processes for financing
		Business process re-engineering
		Paradigm shift towards financial automation
		Blockchain implementation framework
		Changes in the financial process tailored to BT
	Flexibility of SSCF	Innovative financing solutions for sustainable production
		Efficiency of financial information flow in the supply chain through blockchain
		Incentive mechanisms for stakeholder participation in blockchain-based financing
		Determining implementable financing strategies in blockchain
		Planning, directing, and controlling the flow of financial resources throughout the sustainable supply chain
		Integration of logistics financial execution processes into a blockchain platform
	Risk Management	Management of financial operational risk levels in the blockchain supply chain
		Integration management between different systems in banking and finance
		Management of risks related to non-compliance and assurance
		Continuous adjustment of risk premiums for financing proposals
Consequences	Financial System Development	Reduction of investment and financing risks
		Increased profitability
		Reduction of company costs
		Improved cash flow circulation
	Achieving Sustainable Goals	Development of environmentally friendly ideas
		Improved environmental performance
		Comprehensive satisfaction

3. Findings and Results

To identify and finalize the variables for the BT model in the context of a sustainable supply chain with an emphasis on finance, the fuzzy Delphi method was employed. Based on the qualitative study and coding, 13 components were initially proposed for the BT model in a sustainable SCF. Subsequently, considering these proposed options and the linguistic variables (Very high: (7, 9, 10); High: (5, 7, 9); Medium: (3, 5, 7); Low: (1, 3, 5); Very Low: (0, 1, 3)) a questionnaire was designed for distribution to experts. The results from the first phase of the expert survey are presented in Table 2.

For the second round of the Fuzzy Delphi expert survey, the second questionnaire was prepared. This questionnaire, along with each expert's previous response and the degree of their disagreement with other experts' views, was re-sent to the expert panel members. In this second stage, the experts responded to the questions again, considering the opinions of other group members. The results are presented in Table 2. Following revisions from the first round, the number of components was reduced to 10 in this second round. Based on the views provided in the first round and by comparing them with the results of this round, if the difference between the two rounds is less than the 0.2 threshold, the survey process is stopped. As the table above shows, the expert panel reached a consensus on some variables. The level of disagreement for these variables in both the first and second rounds was less than the 0.2 threshold, thus stopping the survey for them. Among the mentioned variables, those with a defuzzified mean of expert opinions less than 8 were to be removed from the conceptual model; however, this did not occur in this round. Therefore, the two components, "Supply Chain Integration" and "Centralized Business Model," will be evaluated in the third round. In the third round, while making the necessary changes to the model components, a third questionnaire was prepared and sent back to the experts along with each individual's previous point of view and the amount of difference between them and the average point of view of other experts. The results are presented in Table 2.

Table 2

Result of the survey rounds

No.	Linguistic value	Very low	Low	Medium	High	Very high	max	mod	min	Non-fuzzy average of expert opinions		
	Numerical value	1	3	5	7	9						
	Components - Fuzzy value	(0,1,3)	(1,3,5)	(5,3,7)	(5,7,9)	(7,9,10)						
Result of the first round of survey												
1	Laws and regulations	15	5	1	0	0	9.62	8.33	6.33	8.2		
2	Stakeholder engagement	15	4	2	0	0	9.52	8.24	6.24	8.1		
3	Standardization	17	3	1	0	0	9.71	8.52	6.52	8.4		
4	Environmental infrastructure	17	2	2	0	0	9.62	8.43	6.43	8.3		
5	Technology management	18	2	1	0	0	9.76	8.62	6.62	8.5		
6	Policymaking	19	1	1	0	0	9.81	8.71	6.71	8.6		
7	Information management	16	4	1	0	0	9.67	8.43	6.43	8.3		
8	Supply chain integration	16	2	3	0	0	9.48	8.24	6.24	8.1		
9	Centralized business model	15	3	3	0	0	9.43	8.14	6.14	8		
10	SSCF flexibility	16	3	2	0	0	9.57	8.33	6.33	8.2		
11	Risk management	17	2	2	0	0	9.62	8.43	6.43	8.3		
12	Development of the financial system	17	3	1	0	0	9.71	8.52	6.52	8.4		
13	Achieving sustainable goals	19	2	0	0	0	9.9	8.81	6.81	8.7		
Result of the second round of survey												
											Difference in the means of the first and second questionnaires	Second round result
1	Laws and Regulatory Framework	16	4	1	0	0	9.67	8.43	6.43	8.3	0.09	Confirm
2	Standardization	18	2	1	0	0	9.76	8.62	6.62	8.5	0.09	Confirm
3	Technology and Infrastructure Management	18	3	0	0	0	9.86	8.71	6.71	8.6	0.1	Confirm
4	Policymaking	19	2	0	0	0	9.9	8.81	6.81	8.7	0.1	Confirm
5	Information Management	17	3	1	0	0	9.71	8.52	6.52	8.4	0.09	Confirm
6	Supply Chain Integration	18	2	1	0	0	9.76	8.62	6.62	8.5	0.37	Third round
7	Centralized Business Model	18	2	1	0	0	9.76	8.62	6.62	8.5	0.45	Third round
8	SSCF Flexibility	17	3	1	0	0	9.71	8.52	6.52	8.4	0.18	Confirm
9	Development of the Financial System	18	2	1	0	0	9.76	8.62	6.62	8.5	0.09	Confirm
10	Achieving Sustainable Goals	19	2	0	0	0	9.9	8.81	6.81	8.7	0	Confirm
Result of the third round of survey												
											Difference in the means of the second and third questionnaires	Third round result
6	Supply Chain Integration	19	1	1	0	0	9.81	8.71	6.71	8.6	0.09	Confirm
7	Centralized Business Model	18	3	0	0	0	9.86	8.71	6.71	8.6	0.1	Confirm

The ISM method is utilized to construct a comprehensive model, define the intricate relationships, and establish a hierarchical structure among the variables identified using a grounded theory paradigm. ISM is particularly effective for analyzing the multifaceted relationships between variables across various levels of influence.

The implementation of the ISM technique typically involves seven critical phases:

1. **Variable Identification:** Initially, all variables pertinent to the problem under investigation are identified.
2. **Structural Self-Interaction Matrix (SSIM) Development:** A matrix is constructed to capture the direct contextual relationships between these identified variables.
3. **Initial Reachability Matrix Derivation:** From the SSIM, an initial reachability matrix is extracted.
4. **Final Reachability Matrix Refinement:** This initial matrix is then transformed and refined to produce the final reachability matrix, which indicates all indirect and direct relationships.
5. **Level Partitioning:** Variables are subsequently categorized into distinct hierarchical levels using the information from the final reachability matrix.
6. **Model Construction:** The ISM model is then graphically represented based on the established levels and relationships.
7. **MICMAC Analysis:** Finally, variables are classified based on their driving power and dependence characteristics through MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) analysis.

These steps will be explained in greater detail in the subsequent sections.

Following the identification of variables, they were meticulously structured within the SSIM. This matrix is designed such that all relevant variables are listed both as rows and columns. The nature of the relationship between any two given variables (e.g., variable *i* and variable *j*) is precisely defined using the following symbolic notations:

- **V:** Indicates that variable *i* leads to (or influences) variable *j*.
- **A:** Indicates that variable *j* leads to (or influences) variable *i*.
- **X:** Denotes a bidirectional relationship, meaning variables *i* and *j* influence each other.
- **O:** Signifies that there is no relationship between variables *i* and *j*.

To systematically complete the SSIM, a structured pairwise comparison questionnaire was employed. A panel of 21 domain experts was consulted to ascertain the degree of influence each model variable exerted on another, following the established guidelines by Bolanos et al. (2005). However, in this study, for level determination, we followed the methodology proposed by Modiri et al. (2017), which utilizes the sum of rows and columns of the final reachability matrix, rather than the traditional set calculations. The calculations are presented in Table 3. Based on these results, the variables in the BT adoption model within the sustainable supply chain environment, with an emphasis on financing, are categorized into 7 distinct levels.

Table 3

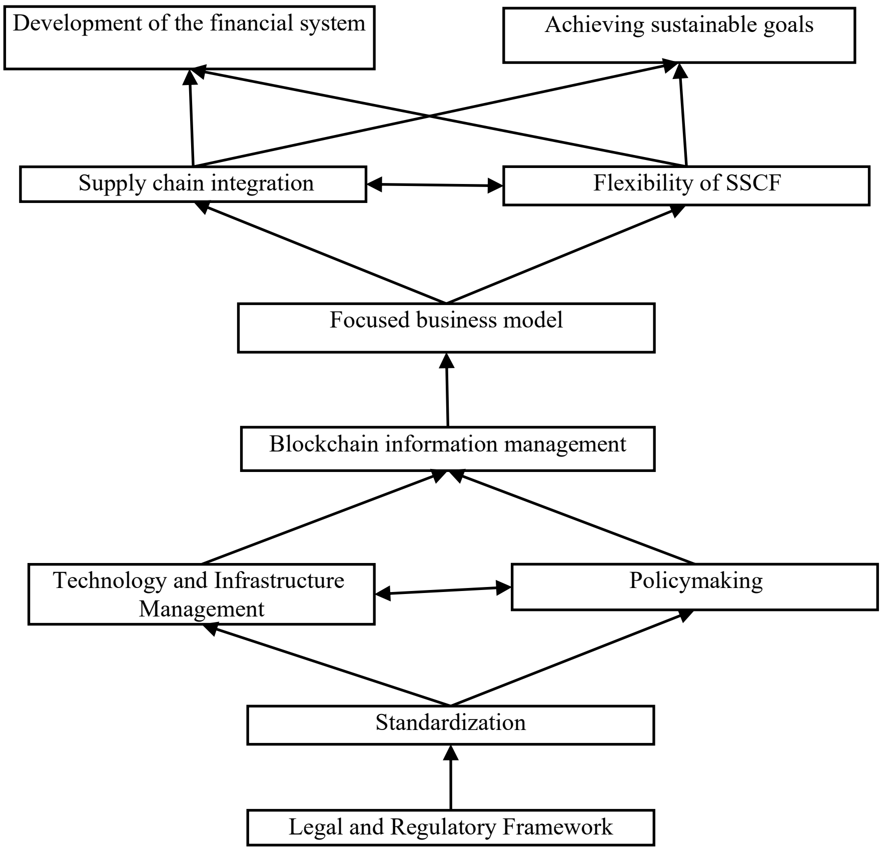
Determining the levels of variables in the BT model in a SSCF

	Impact	Susceptibility	Intensity of impact	Level	Outcome
Financial System Development	1	9	-8	1	Dependent
Achieving Sustainable Goals	1	9	-8	1	Dependent
Supply Chain Integration	4	8	-4	2	Dependent
SSCF Flexibility	4	8	-4	2	Connected
Centralized Business Model	5	6	-1	3	Connected
Blockchain Information Management	6	5	1	4	Connected
Technology and Infrastructure Management	8	4	4	5	Independent
Policy Making	8	4	4	5	Independent
Standardization	9	2	7	6	Independent
Legal and Regulatory Framework	10	1	9	7	Dependent

Following the determination of variable relationships and levels, a hierarchical structural model was constructed using the data from Table 2. For this purpose, variables were arranged hierarchically from top to bottom based on their assigned levels. This structural representation is depicted in Figure 3. As seen, the ISM depicts a 7-level hierarchy. At the foundational (seventh) level is the variable "Regulatory and Legal Framework." This variable is the most influential, acting as the root cause, and is critical for initiating the adoption of BT in sustainable supply chain financing. This finding highlights the critical role of government in establishing and supporting a robust legal and regulatory environment and infrastructure. Consequently, for managers aiming to foster BT adoption in sustainable supply chain financing, this variable should be the primary focus. At the sixth level is "Standardization," which influences variables at the next level. Level five contains two variables: "Technology and Infrastructure Management" and "Information Management." These variables not only have a bidirectional relationship with each other but also influence the subsequent levels. At the fourth level, "Information Management" continues to influence subsequent variables in the structural model. The third level includes the "Centralized Business Model," which affects its subsequent variable. At the second level, "Flexibility of SSCF" and "Supply Chain Integration" are present, influencing the variables at the first level. Finally, at the first (highest) level, "Achievement of Sustainable Goals" and "Development of the Financial System" are identified as outcome variables, primarily influenced by the variables at lower levels. In summary, the "Regulatory and Legal Framework" emerges as the most critical and influential variable for successful BT adoption in sustainable supply chain financing. Its immediate improvement is paramount, as the overall adoption of BT in this context is heavily contingent upon its strength.

Figure 3

ISM model of BT within a SSCF



The MICMAC analysis aims to identify and analyze the driving power and dependence of variables within a system. In this analysis, variables are categorized into four distinct clusters based on their driving and dependence power. Figure 4 illustrates the driving and dependence power of the BT model within the sustainable supply chain context, with a specific focus on financing.

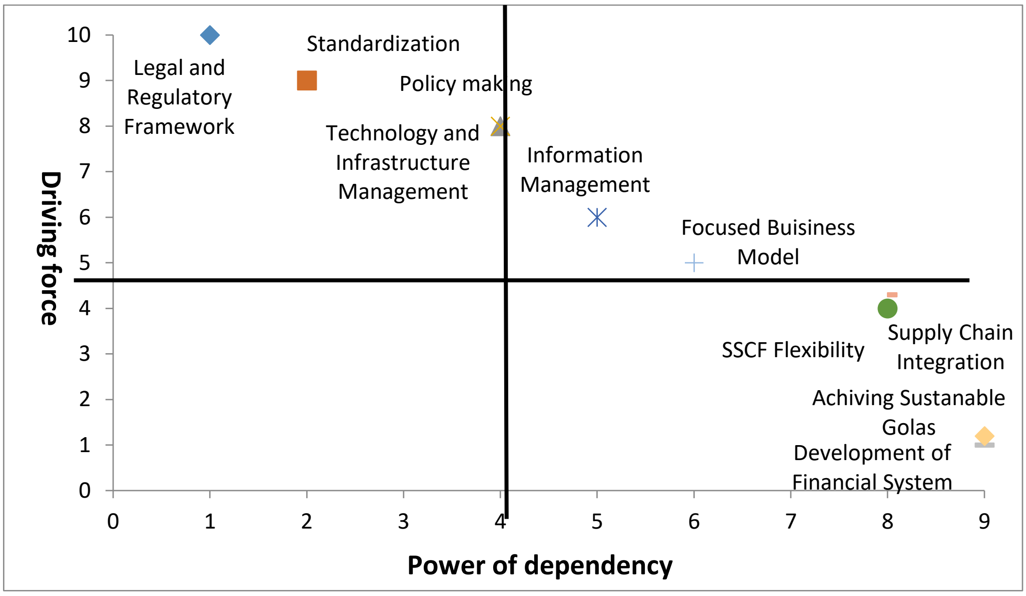
1. Cluster 1: Autonomous Variables (Weak Driving Power, Weak Dependence). These variables are self-contained and have the least influence on the

overall model. Notably, our analysis found no variables falling into this category, indicating a high degree of interconnection among the variables in our model.

2. Cluster 2: Dependent Variables (Weak Driving Power, High Dependence). This cluster includes variables that are strongly influenced by others but have limited power to influence the system themselves. In our model, the variables "Development of Financial System," "Achievement of Sustainable Goals," "Supply Chain Integration," and "Flexibility of Sustainable Supply Chain Financing" belong to this category.
3. Cluster 3: Linkage/Relay Variables (High Driving Power, High Dependence). These variables act as critical connectors, as they both strongly influence and are strongly influenced by other variables. Any intervention on these variables can have significant ripple effects throughout the system. The variables "Centralized Business Model" and "Information Management" fall into this crucial intermediary category.
4. Cluster 4: Driving Variables (High Driving Power, Weak Dependence). These are the key variables that exert strong influence over the entire system. They are the primary drivers of change and have relatively low dependence on other variables. The variables "Technology and Infrastructure Management," "Policy Making," "Standardization," and "Legal and Regulatory Framework" are identified in this influential category.

Figure 4

MICMAC model of BT within a SSCF



This study employs a Fuzzy Cognitive Map (FCM) within an interpretive-structural framework, selected over Structural Equation Modeling (SEM) to effectively model bidirectional relationships. The methodology involved several stages:

1. Structural Matrix Formation: Initial mapping of inter-relationships.
2. Quantification and Refinement: Determining causal intensity and eliminating redundant or inverse relationships by comparing power matrix values against a single numerical scale (e.g., 42, derived from expert input thresholds).
3. Fuzzification: Converting numerical vectors into fuzzy sets (between 0 and 1) to create a fuzzy matrix of cause-and-effect relationships (Table 4), with specific response limits (21-63) to mitigate expert bias.
4. Harmonic Proximity Analysis: Utilizing this method with an access matrix for comprehensive analysis.

Using fuzzy pairwise comparison and UcinetSetup software, the study developed an FCM for a BT model in a SSC, with an emphasis on financing. The map illustrates direct and positive causal relationships, where line thickness indicates influence strength. Key Findings show that the "legal and regulatory framework" emerged as the most influential factor, impacting all other variables. Harmonic centrality analysis confirmed this, placing it at the highest level (level 1), indicating maximum connectivity and the shortest path to other nodes. Furthermore, "Financial system development" and "achieving sustainable goals" were identified as the most dependent variables, receiving the most influence. They ranked lowest in centrality (level 9), suggesting less direct information sharing; their improvement is contingent on strengthening upstream causal factors. Successful blockchain technology adoption requires an initial focus on the "legal and regulatory framework," "standardization," and "policy-making." These findings provide valuable insights, particularly for the structural equation modeling sector.

Table 4

Fuzzy matrix of the strength of cause-and-effect relationships between variables

		1	2	3	4	5	6	7	8	9	10	Impact
Legal and Regulatory Framework	1		0.57	0.74	0.64	0.76	0.83	0.79	0.64	0.55	0.52	9
Standardization	2			0.55	0.64	0.86		0.93	0.9	0.52	0.86	7
Technology and Infrastructure Management	3				0.6	0.62	0.76		0.5	0.67	0.86	6
Policymaking	4			0.81		0.86	0.69	0.76	0.79	0.76	0.81	7
Blockchain information management	5						0.6	0.5	0.86	0.76	0.79	5
Supply chain integration	6								0.67	0.62	0.79	3
Focused business model	7						0.64		0.81		0.52	3
Flexibility of SSCF	8						0.52			0.52		2
Development of the financial system	9											0
Achieving sustainable goals	10											0
		0	1	3	3	4	6	4	7	8	7	

In this section, the final model obtained from the ISM method was tested using structural equations. To test the specified relationships between the model variables, which were designed through the comprehensive ISM method, the Partial Least Squares (PLS) method was utilized. To assess the reliability of the research constructs, two criteria, Composite Reliability (CR) and Cronbach's Alpha, were used as shown in Table 5. The Cronbach's Alpha for all variables was greater than10 0.7, thus confirming reliability. The Composite Reliability (CR) values were also greater than the threshold of 0.7 in all cases, indicating satisfactory construct reliability.

Table 5

Reliability of research constructs

	Cronbach's alpha	Combined Reliability (CR)
Standardization	0.957	0.967
SSCF Flexibility	0.899	0.923
Development of the Financial System	0.875	0.915
Achieving Sustainable Goals	0.855	0.912
Organizational Policymaking	0.923	0.937
Centralized Business Model	0.923	0.939
Blockchain Information Management	0.925	0.940
Technology and Infrastructure Management	0.928	0.942
Legal and Regulatory Framework	0.960	0.968
Supply Chain Integration	0.971	0.976

Subsequently, divergent validity (also known as discriminant validity) was examined to assess the fit of the measurement models in the PLS method, as shown in Table 6. The results pertaining to the discriminant validity of the constructs also demonstrate the confirmation of the items. The interpretation is that if all numbers on the main diagonal are greater than the numbers directly below and to their right, the model possesses appropriate discriminant validity.

Table 6

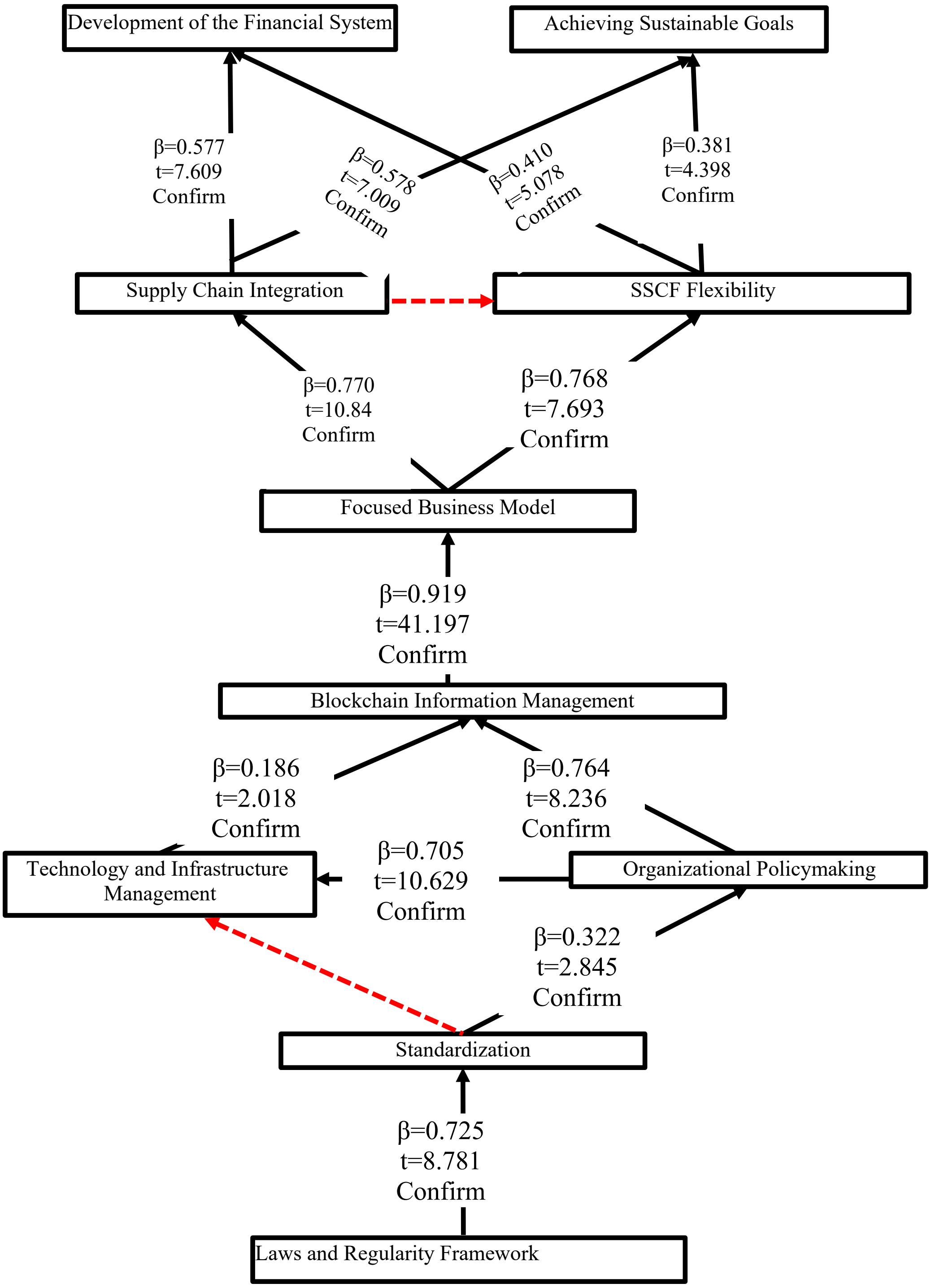
Correlation coefficients and divergent validity between research variables

	1	2	3	4	5	6	7	8	9	10
Standardization	0.925									
SSCF Flexibility	0.357	0.817								
Development of the Financial System	0.337	0.801	0.855							
Achieving Sustainable Goals	0.361	0.803	0.805	0.880						
Organizational Policymaking	0.322	0.798	0.781	0.876	0.807					
Centralized Business Model	0.442	0.774	0.857	0.830	0.831	0.828				
Blockchain Information Management	0.394	0.730	0.837	0.897	0.794	0.719	0.832			
Technology and Infrastructure Management	0.212	0.677	0.676	0.581	0.700	0.722	0.721	0.837		
Legal and Regulatory Framework	0.725	0.191	0.155	0.153	0.202	0.233	0.187	0.071	0.913	
Supply Chain Integration	0.220	0.730	0.776	0.856	0.726	0.770	0.818	0.648	0.016	0.922

The evaluation of the SEM revealed the statistical significance of 12 out of 14 hypothesized relationships between various constructs. Most confirmed relationships showed a positive and significant effect, connecting "Regulatory Framework" to "Standardization," "Standardization" to "Organizational Policymaking", "Organizational Policymaking" to "Technology and Infrastructure Management" and "Blockchain Information Management," "Technology and Infrastructure Management" to "Blockchain Information Management," "Blockchain Information Management" to "Centralized Business Model," "Centralized Business Model" to "Supply Chain Integration" and "Sustainable Supply Chain Financing Flexibility," "Supply Chain Integration" to "Financial System Development" and "Achievement of Sustainable Goals," and "Sustainable Supply Chain Financing Flexibility" to "Financial System Development" and "Achievement of Sustainable Goals". However, two relationships were not statistically confirmed due to t-statistics below 1.96: the effect of "Standardization" on "Technology and Infrastructure Management," and the effect of "Supply Chain Integration" on "Sustainable Supply Chain Financing Flexibility." The empirically confirmed model, including factor loadings (β) and t-statistics, is presented in Figure 5.

Figure 5

Validation of BT within a SSCF



4. Discussion and Conclusion

The present research proposed and validated a blockchain technology (BT) model to support sustainable supply chain finance (SSCF) in the automotive parts manufacturing industry (APMI). Through an integrated mixed-methods approach, combining grounded theory, fuzzy Delphi, interpretive structural modeling (ISM), fuzzy cognitive mapping (FCM), and partial least squares structural equation modeling (PLS-SEM), the study uncovered a seven-level hierarchy of factors influencing blockchain adoption and sustainable financial performance. The analysis highlighted that the legal and regulatory framework forms the foundational driver enabling standardization, policymaking, and technological infrastructure, while the centralized business model, supply chain integration, and flexibility of SSCF emerged as intermediate enablers leading to the ultimate outcomes of achieving sustainable goals and development of the financial system.

A key empirical finding is the pivotal role of the legal and regulatory framework as the most influential and least dependent variable, confirmed both by ISM and FCM. This aligns with prior literature emphasizing that robust legal environments are indispensable for blockchain diffusion and risk reduction (Choi, 2020; Zhou & Masi, 2025). In supply chain finance contexts, a clear legal status for blockchain records and smart contracts underpins trust and enforceability, allowing participants to shift from paper-based or fragmented digital solutions to a unified ledger (Agarwal et al., 2022). Similarly, the results echo work indicating that regulatory support and governance frameworks are prerequisites for large-scale blockchain uptake in sustainable finance (Guo et al., 2024). Without explicit policies and licensing mechanisms, firms face barriers around compliance and liability that stall investment (Öztürk & Yildizbaşi, 2020).

The second level in the hierarchy—standardization—proved essential for interoperability and data consistency across multi-tiered automotive supply networks. SEM confirmed the strong positive effect of the regulatory environment on standardization. This is coherent with research showing that harmonized data protocols, security standards, and accounting frameworks are decisive for cross-organizational blockchain platforms (Safaei Ghadikalai & Vedadi, 2015; Tseng et al., 2019). The validated link from standardization to organizational policymaking further illustrates that when shared norms exist, firms are more willing and able to set internal policies aligning technology, sustainability, and finance (Martiny et al., 2024). Earlier studies also stressed that internal governance strategies, when grounded in external standards, can accelerate sustainable supply chain transformation (Parung, 2019).

The study found technology and infrastructure management and blockchain information management to be tightly connected drivers of transparency, traceability, and secure financial data flow. These findings confirm prior evidence that technical readiness, data reliability, and integration capacity are crucial enablers for blockchain-based SSCF (Alazab et al., 2021; Aslam et al., 2021). By establishing reliable data pipelines and privacy-preserving yet auditable ledgers, firms can overcome one of the largest SSCF obstacles—lack of real-time, verifiable sustainability and financial data (Hofmann & Sertori, 2020). Effective information management, in turn, was shown to fuel the centralized business model, indicating that technology maturity underpins the redesign of value creation logic around distributed ledger capabilities (Duan et al., 2023; Guo et al., 2024).

One of the most significant contributions of this research is clarifying the role of a centralized blockchain-centric business model as a linking variable with both high driving and high dependence power. This result complements previous conceptual calls to redefine business processes and financial flows to leverage blockchain's smart contracts and disintermediation benefits (Cao et al., 2023). In APMI, where supplier networks are heterogeneous and payment cycles long, a blockchain-centered model can embed green financing incentives directly into transactional workflows (Queiroz et al., 2021). The strong empirical links from this variable to supply chain integration and SSCF flexibility illustrate how business model innovation enables seamless multi-party collaboration and adaptive financing terms based on verified sustainability data (Fathi & Sadeghi, 2021).

Moving upward, the study verified that supply chain integration and SSCF flexibility are crucial proximate enablers for sustainable outcomes. Integrated chains allow real-time information exchange and collective risk management, a key SSCF requirement previously observed in case studies of sustainable automotive logistics (Wellbrock et al., 2020). Flexible financing, when coupled with blockchain, helps tailor credit and payment terms to sustainability performance, echoing prior models where transparent ESG data reduced credit risk and incentivized eco-innovation (Guo et al., 2024; Slavinskaitė et al., 2025). Interestingly, two hypothesized paths—standardization to technology and supply chain integration to SSCF flexibility—were not statistically significant, implying that simply having shared norms does not guarantee technical readiness, and that integrated operations do not automatically produce flexible finance without deliberate model redesign. This nuance extends previous frameworks by showing the need for active organizational change beyond passive integration (Asante Boakye et al., 2025).

Finally, the validated positive effects of supply chain integration and SSCF flexibility on financial system development and achievement of sustainable goals confirm the central thesis of SSCF: that aligning financing with sustainability enhances both environmental and economic performance (Tseng et al., 2019; Zhou & Masi, 2025). Blockchain strengthens this by reducing fraud, streamlining settlements, and embedding ESG metrics into funding decisions (Agarwal et al., 2022). The study thus provides robust empirical evidence that BT-enabled SSCF can break the vicious cycle of cash constraints hindering green investment, a long-standing problem for small and medium automotive suppliers (Mangan & Lalwani, 2016; Masoumi et al., 2019).

Theoretically, the research advances SSCF and blockchain integration by providing a multi-level, empirically validated adoption model tailored to the APMI. Unlike prior conceptual works (Choi, 2020; Queiroz et al., 2021), the present model links regulatory and technological prerequisites to intermediate organizational redesign and final sustainability outcomes, bridging an important gap in SSCF scholarship. Practically, the findings guide managers to focus first on governance and standardization, then on internal policy and IT capacity, before attempting business model overhaul and chain-wide financial integration.

This study's cross-sectional design restricts the ability to infer long-term causal dynamics between the identified constructs. Data were collected predominantly from Iranian automotive parts manufacturers, which may limit generalizability to other sectors or geographies with different regulatory and technological contexts. The reliance on expert judgment in the qualitative and ISM/FCM phases, while necessary for exploratory modeling, introduces potential bias due to subjective interpretation. Additionally, because blockchain and SSCF remain emergent in many markets, some constructs lacked abundant local empirical benchmarks, possibly influencing factor interpretation and weighting.

Future studies could adopt longitudinal or panel data to track how regulatory and technological maturity influence blockchain-enabled SSCF outcomes over time. Comparative cross-country analyses could reveal how differences in legal frameworks and industrial digitalization affect adoption pathways. Researchers might also test the model in other manufacturing sectors, such as electronics or aerospace, to assess external validity. Experimental and simulation-based designs could explore how alternative incentive mechanisms or tokenized financing influence supplier sustainability behavior. Finally, integrating behavioral adoption models with the structural ISM-SEM approach could yield deeper insights into organizational change and trust formation.

Practitioners should first secure regulatory clarity and standards alignment before investing heavily in blockchain platforms. Firms are advised to develop internal governance and technology strategies in parallel, ensuring reliable data pipelines and cybersecurity. Automotive parts manufacturers can pilot centralized blockchain finance models on limited supplier groups to demonstrate value and build trust. Collaboration with banks and fintechs to design flexible, ESG-linked financing will help unlock capital for sustainability upgrades. Ultimately, a staged adoption roadmap—from legal groundwork and standardization through to integrated, incentive-compatible finance—offers the most effective path toward resilient and sustainable supply chains.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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