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Blockchain Adoption Drivers for Circular Supply Chain Management in Manufacturing: A DEMATEL–ISM–MICMAC Analysis

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While blockchain technology has the potential to improve transparency, traceability and resource circularity, its implementation in circular supply chains has been affected by the interrelated technological, organizational, financial, regulatory and sustainability factors. In this paper, the authors propose the design of an integrated framework of DEMATEL, ISM and MICMAC for the identification of causal relationships, the creation of hierarchy of interrelationships and the categorisation of the driving and the dependence characteristic of the 18 influencing factors. The findings reveal that the factors of regulatory support, environmental sustainability pressure, and blockchain infrastructure availability are among the key drivers that shape the foundation. Product traceability, digital product passports, integration of reverse logistics, remanufacturing certification, and customer acceptance are the outcomes that are mainly dependent in the process of adoption, whereas financial investment, top management commitment, digital readiness and skilled workforce are some of the supporting factors. To systematically explain how the blockchain adoption factors interact and influence the implementation of circular supply chains, the study combines three complementary structural modelling techniques to provide a prioritized framework for managerial decisions and policy development.

Keywords: Blockchain adoption, Circular economy, DEMATEL, Digital readiness, ISM

Introduction

Background

Manufacturing industry is moving towards the paradigm of Circular Economy (CE), which is an economic model based on the principles of resource efficiency and reduction of waste, re-use, repair, refurbishment, remanufacture and recycling. The concept of the CE is to keep products, components and materials in the economy for as long as possible to minimise environmental impacts and reliance on virgin materials.[1,2] For successful implementation of CE in industrial systems, a successful coordination between manufacturers, suppliers, logistics providers, remanufacturers and recyclers is essential. One of the key requirements for the circular approach to manufacturing is having accurate origin data, material composition data, ownership information, maintenance data and end-of-life recovery data. In this context, traceability, transparency and reverse logistics have emerged as key attributes for circular supply chain management.[3,4] Reverse logistics systems help the recovery, inspection, remanufacturing and recycling of returned products, which helps to achieve closed-loop material flows and sustainable operation.

Blockchain technology has become an exciting digital tool to support sustainable manufacturing and circular supply chains in recent years.[5] Hence, blockchain is recognized as a promising technology that can better enable trust, accountability and sustainability in manufacturing ecosystems by combining it with Industry 4.0 technologies, including the Internet of Things (IoT), RFID, and digital product passports.[6,7]

Industrial Problem

Although the potential advantages of blockchain-based circular systems exist, there are some operational and managerial challenges for manufacturing industries. Poor product traceability is one of the most important problems, as it is difficult to trace products and components through different phases of their lifecycle due to incomplete or

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fragmented records. Where product traceability is critical, like in automotive, aerospace, heavy engineering, or industrial equipment manufacturing, the consequences of inadequate traceability are evident: product quality issues and regulatory compliance concerns.

A key issue is the availability of counterfeit spares that may lead to loss of reliability, safety, maintenance performance and reliability of the equipment. Some solutions have been proposed for counterfeit product control based on a blockchain serialization and immutable transaction records in conventional information systems.

Manufacturers also experience inefficient reverse logistics systems that involve slow product returns, poor visibility of returns, high returns recovery costs, and weak coordination between supply chain parties. In addition, there is a lack of information sharing between actors during the life cycle, meaning that maintenance information, usage conditions, and material information are often not available and/or not accessible for effective remanufacturing, refurbishment and recycling decisions.[8]

A related problem is that it is hard to confirm remanufactured products. Customer and user trust in the quality, performance and service history of remanufactured components is often low, affecting their uptake into the market and the expansion of circular business. Overall, these issues can impede the shift towards digitally supported circular manufacturing systems.

Research Gap

Previous research on blockchain and circular economy has been mainly conceptually based, literature review, technology frameworks, and empirical adoption studies[5,7] but limited understanding of the interrelationships of the various adoption factors and the structural hierarchy for implementing blockchain in the circular manufacturing environment. Previous studies focus on one technological, organizational or environment factor at a time, and fail to adequately reflect the causal relationships between the three factors.

Furthermore, the causal analysis and structural modeling techniques in relation to the evaluation of blockchain adoption in circular manufacturing supply chains are lacking in the literature, especially in emerging economies and industrial sectors where resource availability and digital maturity are very different. The combination of the DEMATEL (Decision-Making Trial and Evaluation Laboratory), ISM (Interpretive Structural Modeling) and MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) may help to achieve a full understanding of driving forces, dependence relationships and hierarchical structures. This integrated approach has been scarcely explored in the blockchain–circular economy literature, however. This is an opportunity to help shape the effective prioritization of management actions and policy-making.

Research Objectives

The following objects have been set to achieve the above research gap in the present study:

1. To determine the factors that are critical for the adoption of blockchain in circular supply chains in manufacturing industries.
2. To use the DEMATEL method to analyse the causal relationships between these factors.
3. To construct a Hierarchy structure of the factors by ISM.
4. To classify the factors according to driving power and dependence power by MICMAC analysis.
5. To make managerial/policy suggestions that foster blockchain-based circular manufacturing systems.

Novelty and Contribution

The study has provided several contributions to the field of circular economy, digital manufacturing and sustainable supply chain management. It first introduces an integrated DEMATEL–ISM–MICMAC model to systematically study factors for the adoption of blockchain in circular manufacturing supply chains. Second, the study is specifically on circular manufacturing supply chains in which reverse logistics, remanufacturing, traceability, and lifecycle data management are major issues for operations. Thirdly, the integrated framework allows for the identification of important drivers that have a strong influence on other adoption factors, and thus give managers and policy makers a practical roadmap. Finally, the study adds to the growing body of literature on the circular economy and blockchain by integrating causal analysis, hierarchical modeling and factor classification in a single decision-support framework for the circular economy.

Research Methodology

The study is conducted using an integrated multi-stage research approach to examine the factors

impacting the adoption of blockchain technology in manufacturing industries. The framework is a synthesis of qualitative identification of the factors and quantitative structural modeling techniques, which guarantees a complete analysis and reliable interpretation of the experts' knowledge. The overall methodology is used similar to what has been applied in sustainability, supply chain, and technology adoption studies.[9,10] The research process (Fig. 1) is outlined as follows:

Identification of Factors

A systematic screening of literature and expert consultation were performed for the identification of factors. The literature review was conducted using the common steps of literature search in the Scopus, Web of Science, and Google Scholar databases from January 2015 to December 2025, followed by the inclusion and exclusion of relevant publications, identification of their relevance, and content analysis.[11] The timeframe was chosen because a number of block chain-based supply-chain applications, as well as research into circular economy, received significant attention over the chosen time period.

The following Boolean search string was used, with some syntax changes depending on the search database:

("blockchain" OR "distributed ledger technology" OR "DLT")AND("circular economy" OR "circular supply chain" OR "closed-loop supply chain" OR "reverse logistics" OR "remanufacturing") AND ("manufacturing" OR "manufacturing industry" OR "industrial supply chain"OR "Industry 4.0") AND ("adoption factor" OR "driver" OR "barrier" OR "challenge" OR "enabler").

Only peer-reviewed journal articles, review articles, conference papers and relevant institutional reports published in English were included. The studies were included if they: (i) studied the adoption of blockchain or a distributed ledger; (ii) discussed or examined manufacturing, supply-chain, circular-economy, reverse-logistics, or remanufacturing contexts; and (iii) identified, discussed, or examined the drivers, barriers, enablers, or implementation challenges of blockchain or distributed-ledger adoption. Studies were excluded if they: (i) did not discuss organizational or supply-chain implications; (ii) did not discuss technical protocols of the blockchain; (iii) were redundant; (iv) lacked full-text information; or (v) did not include relevant evidence of the factors for blockchain adoption.

The relevance assessment process took place in 3 steps. The first step was screening titles/keywords for obvious irrelevancy. Second, abstracts were screened

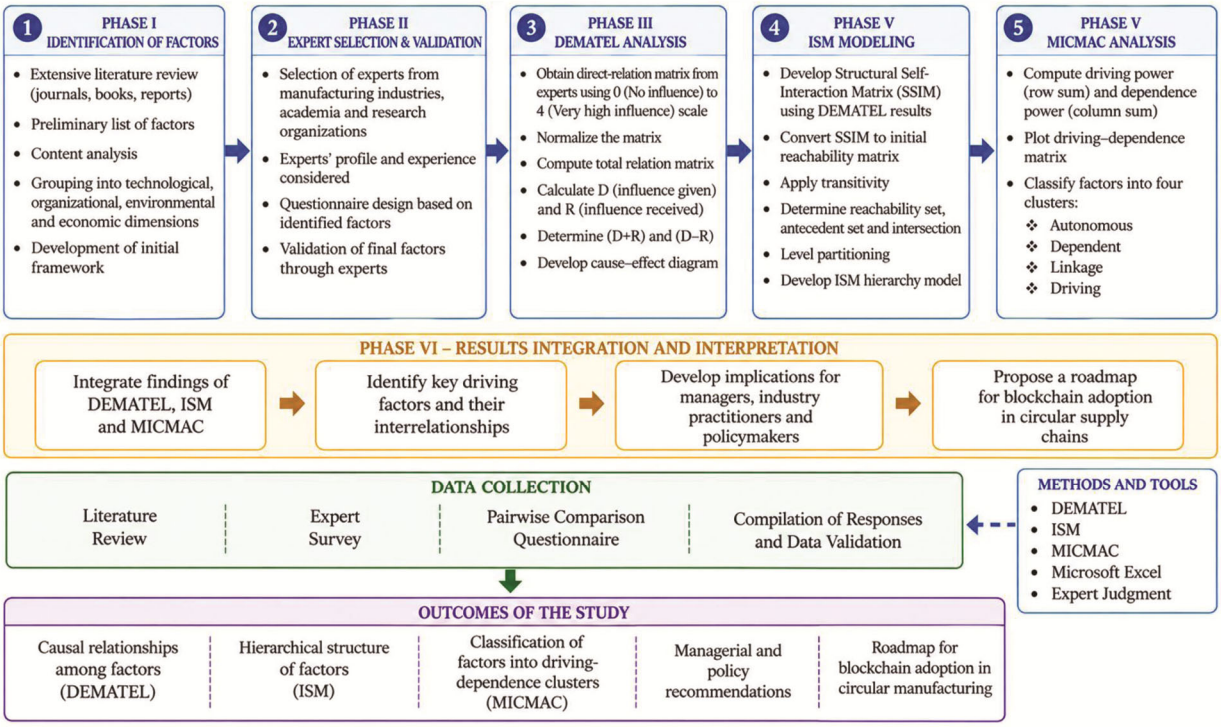


Fig. 1 — Research methodology

for inclusion and exclusion based on inclusion and exclusion criteria. Finally, all of the potentially relevant studies were reviewed for candidate factors. Similar and overlapping factors were merged and ambiguous factors were further clarified using expert consultation. Finally, the factors taken into consideration in this study were validated through the consensus of the expert panel, and the resulting list was used for the DEMATEL–ISM–MICMAC analysis.[12] The final factors considered in this study are provided in Table 1.

Expert Panel

Expert judgment was employed for validating the identified factors and also to get input for the comparisons between factors in DEMATEL, ISM, and MICMAC analyses. The use of expert panels is recommended throughout technology adoption, and decision-making studies in contexts with low amounts of empirical information and high levels of context knowledge.[26,27] The expert panel consisted of members from manufacturing industries, academia, and other related fields for the current study.

Selection criteria for experts were developed to guarantee reliability and relevance of the knowledge gathered judgments. The criteria were: (i) at least 5 years professional or research experience; (ii) direct involvement in the field; and (iii) prior experience with management, or digital transformation projects (iv) willing to participate in multiple rounds of evaluation[27,28]

Sampling was used to choose experts with special knowledge pertinent to the research goals.[29] The panel of 7 experts was formed as shown in Table 2. The variety of backgrounds of the evaluators brought balanced evaluation and minimized influence.

Table 1 — Identified factors, categories, and supporting literature

Code	Factor	Factor category	Description[Ref]
F1	Product traceability	Technological	Tracking of products, components and materials.[5,6,8]
F2	Digital product passport	Technological	Digital database of products' lifecycle, maintenance and material data[7,13]
F3	Smart contract capability	Technological	Automation of transactions and contractual terms on blockchain[5,14]
F4	Data security and privacy	Technological	Security of critical data on blockchain systems[15]
F5	Interoperability with ERP/IoT systems	Technological	The ability of blockchain to integrate with current enterprise and IoT systems[16]
F6	Blockchain infrastructure availability	Technological	Access to blockchain platforms, networks and digital infrastructure[15,16]
F7	Scalability and system performance	Technological	The efficiency of blockchain systems to process a large volume of industrial transactions[15,16]
F8	Top management commitment	Organizational	Strategic support and leadership in blockchain adoption efforts[17]
F9	Skilled workforce	Organizational	Personnel who have knowledge of blockchain, digital manufacturing and analytics18,19
F10	Organizational digital readiness	Organizational	Existing level of digital maturity and readiness for technology adoption[17,20]
F11	Reverse logistics integration	Operational	The integration of return, recovery, remanufacturing and recycling processes[21]
F12	Supplier collaboration	Operational	The level of information exchange and collaboration between supply chain partners[22,23]
F13	Financial investment	Economic	Funding for blockchain infrastructure, integration and maintenance[20]
F14	Regulatory support	Environmental & regulatory	Government policies, standards and laws encouraging the use of blockchain[24]
F15	Standardization of data and processes	Environmental & regulatory	Common standards for exchange and interoperability of data, and traceability[24]
F16	Remanufacturing certification	Sustainability	Verification and certification of remanufactured products and recovered parts[25]
F17	Environmental sustainability pressure	Sustainability	Pressure to enhance environmental performance, resource efficiency and circularity[1,2]
F18	Customer awareness and acceptance	Market	Trust, awareness, and willingness of customers for adopting the circular product based on blockchain[13,20]

Table 2 — Expert profile

Expert	Sector	Professional role	Organizational background	Experience (years)
E1	Industry	Senior Production Manager	Large-scale manufacturing firm	18
E2	Industry	Supply Chain Manager	Automotive-component manufacturer	15
E3	Industry	ERP/IT Manager	Electronics manufacturing firm	12
E4	Industry	Maintenance and Operations Manager	Process manufacturing firm	14
E5	Industry	Remanufacturing Professional	Remanufacturing and reverse-logistics firm	10
E6	Academia	Associate Professor/Researcher	Engineering higher-education institution	13
E7	Academia	Associate Professor/Researcher	University/research institution	11

DEMATEL Procedure

The DEMATEL (Decision-Making Trial and Evaluation Laboratory) method was employed to analyze the causal relationships among the identified factors influencing blockchain adoption in circular manufacturing supply chains.[30] DEMATEL enables the identification of both direct and indirect influences among factors and classifies them into cause and effect groups.

Step 1: Initial direct-relation matrix

Experts evaluated the influence of factor *i* on factor *j* using a predefined scale ranging from 0 (no influence) to 4 (very high influence). The individual direct-relation matrices obtained from the experts were combined element-wise using the mode. Thus, for each relationship from factor i to factor j, the influence score selected most frequently by the experts was retained.

$$z_{ij} = \text{Mode}\left(z_{ij}^{(1)}, z_{ij}^{(2)}, \ldots, z_{ij}^{(p)}\right)$$

$$z_{ij} = \text{Mode}\left(z_{ij}^{(1)}, z_{ij}^{(2)}, \ldots, z_{ij}^{(p)}\right)$$

$$X = [x_{ij}]_{n\times n} \quad \ldots (1)$$

where, zij is the influence score assigned by expert k, and p is the number of experts, Xij is the degree of influence of factor i on factor j, and n representing number of factors. In the case of more than one modal value, the experts were consulted to reach a consensus value. The aggregated expert judgments form the initial direct-relation matrix **X** as per Eq. (1)**.**

Step 2: Normalization

The initial matrix was normalized to obtain matrix **N** as per Eq. (2)**:**

$$N = \frac{X}{\max_i\left(\sum_{j=1}^{n} x_{ij}\right)} \quad \ldots (2)$$

The normalization process ensures that all matrix elements lie within the range [0,1].

Step 3: Total relation matrix

The total relation matrix **T**, representing both direct and indirect relationships among factors, was calculated as per Eq. (3):

$$T = N(I - N)^{-1} \quad \ldots (3)$$

Where **I** is the identity matrix.

Step 4: Prominence

The row sum (**D**) and column sum (**R**) were determined as per Eq. (4):

$$D_i = \sum_{j=1}^{n} t_{ij} \quad R_i = \sum_{j=1}^{n} t_{ji} \quad \ldots (4)$$

The prominence value of each factor was computed as per Eq. (5):

$$\text{Prominence}_i = D_i + R_i \quad \ldots (5)$$

The more prominent a factor is, the more important it is in the system as a whole.

Step 5: Relation

The relation value was calculated as per Eq. (6).

$$\text{Relation}_i = D_i - R_i \quad \ldots (6)$$

- If (Di–Ri)>0, the factor belongs to the **cause group**.
- If (Di–Ri)<0, the factor belongs to the **effect group**.

The prominence value and the relation value were then plotted on a DEMATEL's cause–effect diagram.

ISM Procedure

ISM[31] was used to build the hierarchy of the factors. ISM models the interrelationships in a structured multilevel model as per following procedure.

Step 1: SSIM development

A Structural Self-Interaction Matrix (SSIM) was developed that was informed by expert judgments on

pairwise relationships among factors. The following four symbols were used:

- **V**: factor *i* influences factor *j*
- **A**: factor *j* influences factor *i*
- **X**: factors *i* and *j* influence each other
- **O**: no relationship exists between factors *i* and *j*.

Step 2: Reachability matrix

Using binary values (1 and 0) as per conventional practice, SSIM was converted to an initial reachability matrix.

Step 3: Transitivity

Transitive rules were used to get the final reachability matrix. If factor A affects factor B and factorB influences factor C, then factor A is assumed to influence factor C. This is the assumption that guarantees logical homogeneity in the hierarchy.

Step 4: Level partitioning

The following sets were identified for each of the following factors:

- **Reachability set**: factors that can be reached from factor *i*.
- **Antecedent set**: factors that can reach factor *i*.
- **Intersection set**: common factors between the reachability and antecedent sets.

The factors whose reachability set and intersection set were the same was given the highest level. After the first set of factors was removed, the process was repeated iteratively until all factors were given a hierarchical level.

Step 5: ISM model construction

A directed hierarchical ISM model was constructed based on the levels obtained from level partitioning step.

MICMAC Analysis

MICMAC analysis was performed using the final reachability matrix obtained from ISM. The objective was to classify factors according to their driving and dependence power.Driving power represents the total number of factors influenced by a particular factor, including itself. Dependence power represents the total number of factors influencing a particular factor. Equations are shown in Eq. (7).

$$DP_i = \sum_{j=1}^{n} r_{ij} \quad DeP_i = \sum_{j=1}^{n} r_{ji} \qquad \ldots (7)$$

where, r_{ij} represents the elements of the final reachability matrix.

Cluster classification

Based on driving power and dependence power, the factors were classified into four clusters:

1. **Autonomous factors** – weak driving power and weak dependence power.
2. **Dependent factors** – weak driving power and strong dependence power.
3. **Linkage factors** – strong driving power and strong dependence power.
4. **Driving factors** – strong driving power and weak dependence power.

The MICMAC classification facilitated the identification of strategic driving factors that strongly influence blockchain adoption in circular manufacturing supply chains and highlighted dependent and linkage factors requiring managerial attention.

Results and Discussion

DEMATEL Results

A DEMATEL analysis was used to explore the interactions between the 18 factors that could affect blockchain adoption in the circular supply chain. The expert evaluations are summarized into a direct-relation matrix (Table 3). The matrix is used to calculate later the DEMATEL and indicates the direct effect of one factor on another. The direct-relation matrix was then normalized to get the total-relation matrix, which includes the direct and indirect effects between the factors. The total-relation matrix obtained is presented in Table 4. The total-relation matrix is used to compute the prominence and causal characteristics of each factor.

The calculated D, R, D+R and D−R values are listed in Table 5. In this case, D+R denotes the importance of a factor with respect to the overall involvement of this factor in the system, while D−R denotes the net causal influence on the system. If the value of D−R is positive, it is a cause-group factor; If it is negative, it is an effect-group factor. From Table 5 it is revealed that the highest prominence (D+R) value is for Interoperability with ERP/IoT systems (F5) with 9.381, followed by Standardization of data and processes (F15) at 8.739, Organizational digital readiness (F10) at 8.364 and Blockchain infrastructure availability (F6) at 8.311. These suggest that the overall interactions of these factors with the other factors in the blockchain adoption system are strong. The D−R values show that the highest causal impact is Regulatory support (F14) with a value of 0.998, followed by Financial investment (F13) with a value

Table 3 — Initial direct-relation matrix

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
F1	0	3	1	2	3	2	1	1	1	2	3	2	1	1	3	2	2	3
F2	3	0	1	2	3	2	1	1	1	2	3	2	1	1	3	3	2	3
F3	2	2	0	3	2	2	2	1	1	2	2	2	1	1	2	2	1	2
F4	2	2	2	0	3	2	2	2	2	2	1	1	2	3	2	1	1	2
F5	3	3	2	3	0	3	3	2	2	3	3	2	2	2	3	2	2	2
F6	2	2	2	2	3	0	3	2	2	3	2	2	3	2	2	1	1	1
F7	2	2	2	2	3	3	0	2	2	3	2	2	3	2	2	1	1	1
F8	2	2	2	2	2	3	2	0	3	3	2	2	3	2	2	1	2	2
F9	1	1	2	2	2	2	2	2	0	3	1	1	2	1	1	1	1	1
F10	2	2	2	2	3	3	2	2	3	0	2	2	2	2	2	1	1	2
F11	3	2	2	1	2	2	1	1	1	2	0	3	1	1	2	3	2	2
F12	2	2	1	1	2	2	1	1	1	2	3	0	1	1	2	3	2	2
F13	2	2	2	2	3	4	3	3	2	3	2	2	0	2	2	1	1	1
F14	2	3	2	3	2	2	2	2	1	2	2	2	2	0	4	3	3	2
F15	3	3	2	2	3	2	2	2	1	2	2	2	2	3	0	3	2	2
F16	2	2	1	1	2	1	1	1	1	1	3	3	1	1	2	0	2	2
F17	2	2	1	1	1	1	1	2	1	1	2	2	1	3	2	2	0	3
F18	2	2	1	1	1	1	1	2	1	2	2	2	1	2	2	2	3	0

Table 4 — Total relation matrix

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
F1	0.192	0.257	0.165	0.206	0.269	0.229	0.174	0.169	0.154	0.234	0.258	0.220	0.168	0.177	0.261	0.214	0.197	0.238
F2	0.263	0.195	0.168	0.209	0.274	0.233	0.177	0.172	0.157	0.238	0.263	0.225	0.171	0.180	0.265	0.239	0.200	0.242
F3	0.219	0.218	0.130	0.215	0.232	0.215	0.184	0.156	0.144	0.219	0.218	0.203	0.157	0.163	0.222	0.196	0.159	0.200
F4	0.234	0.234	0.188	0.164	0.270	0.233	0.199	0.192	0.179	0.237	0.211	0.195	0.193	0.220	0.239	0.187	0.172	0.213
F5	0.308	0.306	0.226	0.272	0.259	0.304	0.260	0.231	0.214	0.309	0.307	0.265	0.232	0.239	0.312	0.254	0.233	0.260
F6	0.251	0.250	0.201	0.223	0.289	0.206	0.235	0.205	0.192	0.276	0.250	0.232	0.229	0.211	0.255	0.200	0.183	0.205
F7	0.251	0.250	0.201	0.223	0.289	0.273	0.168	0.205	0.192	0.276	0.250	0.232	0.229	0.211	0.255	0.200	0.183	0.205
F8	0.257	0.256	0.206	0.228	0.274	0.278	0.218	0.166	0.218	0.283	0.256	0.239	0.234	0.217	0.261	0.207	0.211	0.233
F9	0.176	0.175	0.162	0.178	0.211	0.199	0.172	0.165	0.111	0.224	0.175	0.163	0.167	0.148	0.179	0.153	0.141	0.158
F10	0.248	0.247	0.199	0.220	0.285	0.268	0.211	0.203	0.210	0.207	0.247	0.230	0.204	0.208	0.252	0.199	0.182	0.224
F11	0.244	0.221	0.175	0.172	0.233	0.216	0.162	0.157	0.144	0.220	0.179	0.230	0.157	0.163	0.225	0.223	0.185	0.204
F12	0.213	0.211	0.147	0.163	0.222	0.206	0.154	0.150	0.138	0.210	0.235	0.154	0.150	0.156	0.214	0.214	0.177	0.195
F13	0.262	0.261	0.210	0.233	0.302	0.306	0.245	0.236	0.201	0.289	0.261	0.243	0.172	0.220	0.266	0.209	0.191	0.214
F14	0.270	0.290	0.212	0.257	0.285	0.263	0.224	0.217	0.178	0.268	0.269	0.250	0.217	0.182	0.317	0.263	0.243	0.246
F15	0.287	0.287	0.209	0.233	0.302	0.260	0.221	0.214	0.176	0.265	0.266	0.247	0.214	0.243	0.225	0.260	0.219	0.242
F16	0.202	0.200	0.138	0.153	0.209	0.173	0.144	0.141	0.129	0.177	0.224	0.210	0.140	0.147	0.203	0.138	0.169	0.185
F17	0.207	0.207	0.143	0.160	0.194	0.179	0.150	0.169	0.134	0.184	0.207	0.194	0.146	0.196	0.211	0.189	0.130	0.213
F18	0.207	0.206	0.143	0.159	0.194	0.179	0.150	0.168	0.134	0.204	0.207	0.193	0.146	0.175	0.210	0.188	0.196	0.146

of 0.995 and Top management commitment (F8) with 0.928 (Table 5). They have more influence on the system than they have from other factors. Regulatory support will help create an institutional structure for blockchain adoption, and financial investment will help develop the infrastructure and organizational skills. The support of top management commitment is other strategic decision making and resource allocation.

System performance (F7) also has a positive D−R value of 0.643, which means that system performance causes the system as a whole. This emphasizes the need for system capacity and performance for the successful application of blockchain in the manufacturing sector. On the other hand, the lowest D−R value is for Reverse logistics integration (F11) with a D−R value of −0.770, followed by Remanufacturing certification (F16) with a value of −0.652, Customer awareness and acceptance (F18) with −0.620 and Supplier collaboration (F12) with −0.616 (Table 5). These factors are thus included in the effect group and their relative influence is more influenced by other factors.

The cause–effect diagram (DEMATEL) provided in Fig. 2 clearly represents the difference between the two groups of causes and effects. The factors whose D−R is positive are placed in the cause group, the factors whose D−R is negative are placed in the effect

Table 5 — Prominence and relation values

	Factor	D	R	D+R	D-R	Group
F1	Product traceability	3.782	4.290	8.072	−0.509	Effect
F2	Digital product passport	3.873	4.272	8.145	−0.400	Effect
F3	Smart contract capability	3.449	3.224	6.673	0.225	Cause
F4	Data security and privacy	3.759	3.668	7.427	0.091	Cause
F5	Interoperability with ERP/IoT systems	4.791	4.591	9.381	0.200	Cause
F6	Blockchain infrastructure availability	4.091	4.220	8.311	−0.128	Effect
F7	Scalability and system performance	4.091	3.448	7.539	0.643	Cause
F8	Top management commitment	4.243	3.315	7.558	0.928	Cause
F9	Skilled workforce	3.057	3.004	6.061	0.054	Cause
F10	Organizational digital readiness	4.044	4.320	8.363	−0.276	Effect
F11	Reverse logistics integration	3.512	4.282	7.794	−0.770	Effect
F12	Supplier collaboration	3.307	3.923	7.230	−0.616	Effect
F13	Financial investment	4.321	3.326	7.647	0.995	Cause
F14	Regulatory support	4.452	3.453	7.905	0.998	Cause
F15	Standardization of data and processes	4.368	4.371	8.739	−0.003	Effect
F16	Remanufacturing certification	3.081	3.733	6.815	−0.652	Effect
F17	Environmental sustainability pressure	3.212	3.371	6.583	−0.159	Effect
F18	Customer awareness and acceptance	3.203	3.823	7.026	−0.620	Effect

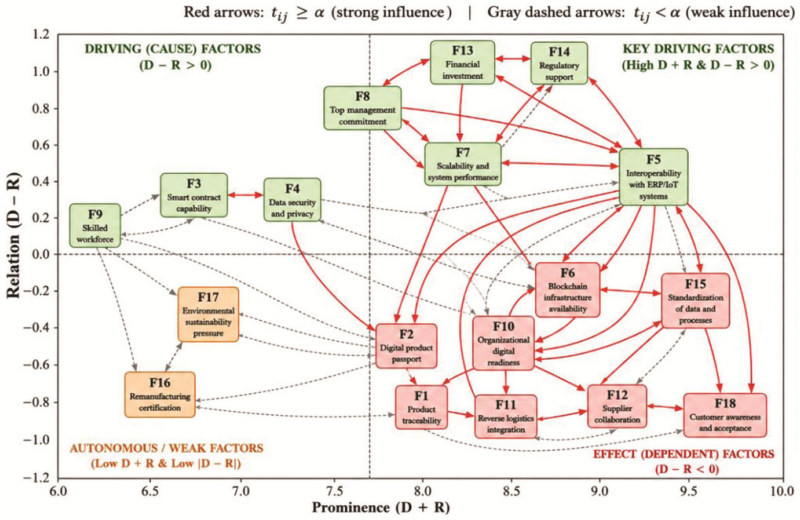


Fig. 2 — Causal diagram

group. The findings suggest that the following causal intervention points should be considered: regulatory support, financial investment, top management commitment, and scalability and system performance. The overall result of the DEMATEL analysis shows that various technology, organizational, financial and institutional factors are mutually dependent and determine the acceptance of blockchain technology for circular supply chains. The outcomes presented in Tables 3 – 5 and Fig. 2 are used to inform the ISM analysis which further clarifies the hierarchical relationships between these factors.

ISM Results

The hierarchical relationships of 18 factors influencing the adoption of blockchain in circular supply chain were established using ISM. First, the SSIM was converted into an initial reachability matrix (Table 6), and then transitivity was added to get the final reachable matrix. The resultant matrix offers the foundation for calculating reachability sets, antecedent sets, and the intersection sets and then determining the hierarchical levels.

The reachability matrix obtained from the final is shown in Table 7. The driving power of the matrix ranges in factors, from 2 to 18. Factors F6, F14 and F17 have the highest driving power (18), while F18 has the lowest driving power (2). The identified factors are not equally influencing the structural development of blockchain enabled circular supply chains.

The results of the level partitioning are given in Table 8. The hierarchical levels were obtained, there

Table 6 — Initial reachability matrix

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
F1	—	X	O	X	A	A	A	A	A	A	X	A	A	A	A	O	A	O
F2		—	X	O	A	A	A	A	A	A	O	A	A	A	A	O	A	O
F3			—	X	A	A	A	A	A	A	O	A	A	A	A	O	A	O
F4				—	A	A	A	A	A	A	O	A	A	A	A	O	A	O
F5					—	A	X	A	A	A	O	A	A	A	A	O	A	O
F6						—	V	X	V	V	V	V	V	X	V	V	X	V
F7							—	A	A	A	O	A	A	A	A	O	A	O
F8								—	X	X	V	V	X	A	V	V	A	V
F9									—	X	V	V	A	A	V	V	A	V
F10										—	V	V	X	A	V	V	A	V
F11											—	A	A	A	A	X	A	O
F12												—	A	A	X	V	A	V
F13													—	A	V	V	A	V
F14														—	V	V	X	V
F15															—	V	A	O
F16																—	A	X
F17																	—	V
F18																		—

Table 7 — Final reachability matrix

Factor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Driving power
1	1	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4
2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
3	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
4	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
5	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	6
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	18
7	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	6
8	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	16
9	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	0	1	14
10	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	15
11	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	3
12	1	1	1	1	1	0	1	0	0	0	1	1	0	0	1	1	0	1	11
13	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	15
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	18
15	1	1	1	1	1	0	1	0	0	0	1	1	0	0	1	1	0	0	10
16	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	3
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	18
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2
Dependence power	15	14	14	14	11	4	11	7	7	7	12	9	6	3	9	12	3	10	168

Table 8 — Level partition table

FN	Reachability set	Antecedent set	Intersection set	Level
1	1,2,4,11,	1,2,4,5,6,7,8,9,10,11,12,13,14,15,17,	1,2,4,11,	I
2	1,2,3,	1,2,3,5,6,7,8,9,10,12,13,14,15,17,	1,2,3,	I
3	2,3,4,	2,3,4,5,6,7,8,9,10,12,13,14,15,17,	2,3,4,	I
4	1,3,4,	1,3,4,5,6,7,8,9,10,12,13,14,15,17,	1,3,4,	I
5	1,2,3,4,5,7,	5,6,7,8,9,10,12,13,14,15,17,	5,7,	II
6	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,	6,8,14,17,	6,14,17,	VI
7	1,2,3,4,5,7,	5,6,7,8,9,10,12,13,14,15,17,	5,7,	II
8	1,2,3,4,5,6,7,8,9,10,11,12,13,15,16,18,	6,8,9,10,13,14,17,	6,8,9,10,13,	IV
9	1,2,3,4,5,7,8,9,10,11,12,15,16,18,	6,8,9,10,13,14,17,	8,9,10,	IV
10	1,2,3,4,5,7,8,9,10,11,12,13,15,16,18,	6,8,9,10,13,14,17,	8,9,10,13,	IV
11	1,11,16,	1,6,8,9,10,11,12,13,14,15,16,17,	1,11,16,	I
12	1,2,3,4,5,7,11,12,15,16,18,	6,8,9,10,12,13,14,15,17,	12,15,	III
13	1,2,3,4,5,7,8,9,10,11,12,13,15,16,18,	6,8,10,13,14,17,	13,	V
14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,	6,14,17,	6,14,17,	VI
15	1,2,3,4,5,7,11,12,15,16,	6,8,9,10,12,13,14,15,17,	12,15,	III
16	11,16,18,	6,8,9,10,11,12,13,14,15,16,17,18,	11,16,18,	I
17	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,	6,14,17,	6,14,17,	VI
18	16,18,	6,8,9,10,12,13,14,16,17,18,	16,18,	I

are six of those. Blockchain infrastructure availability (F6), Regulatory support (F14), Environmental sustainability pressure (F17) are included in Level VI. These are the lowest level of the ISM hierarchy as they have a wide reachability and multiple factors at higher levels which they influence.

Financial investment (F13) is part of Level V. This location suggests that the financial resources are an important mediator linking the basic conditions and the organizational capabilities. Good investment is needed to build the blockchain infrastructure, integrate digital systems and to encourage staff development. The remaining components of Level IV include Top management commitment (F8), Skilled workforce (F9), and Organizational digital readiness (F10). These factors are the organizational skills needed to convert financial and infrastructural investments into real blockchain implementation. Their position highlights the importance of managerial support, employee competencies, and organizational preparedness in adopting blockchain technology.

The Supplier collaboration (F12) and Standardization of data and processes (F15) are involved in Level III. These factors offer a crucial link between organizational capability and supply-chain implementation. Inter-organizational information exchange is fostered through supplier collaboration and consistent and interoperable information sharing is achieved through standardization. There are two factors in Level II: Interoperability with ERP/IoT systems (F5) and Scalability and system performance (F7). These aspects relate the capacities of the organizations and the supply chains and their operationalization of blockchain. From their vantage point it's clear that blockchain use will need to align with current digital systems and be able to meet the performance demands of manufacturing supply chains.

The nodes at level 1 are Product traceability (F1), Digital product passport (F2), Smart contract capability (F3), Data security and privacy (F4), Reverse logistics integration (F11), Remanufacturing certification (F16) and Customer awareness and acceptance (F18). The factors at the top level are more sensitive than those at the lower level. The reachability and intersection sets as presented in Table 8 are consistent with this classification. Hierarchically these six levels are shown in the ISM hierarchical model (Fig. 3). The progression of the drivers from level VI towards the outcome at level I is very clear for the model, which means that product traceability, digital product passports, integration of reverse logistics and remanufacturing certification are not to be regarded on their own. Proper implementation relies on the availability of proper

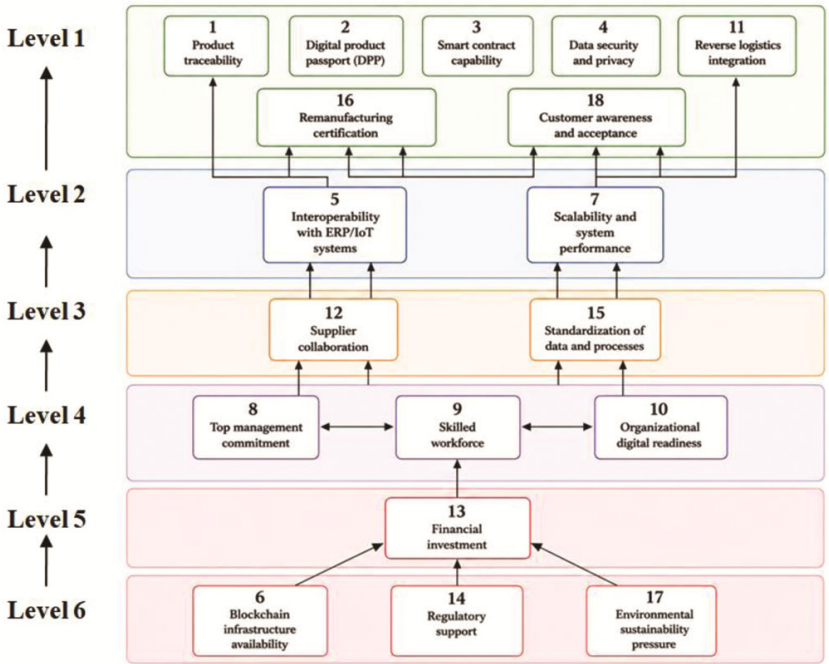


Fig. 3 — ISM hierarchical model

infrastructure, regulatory support, financial resources, organizational capabilities, standardisation, collaboration and technological integration.

The ISM analysis shows that the adoption of blockchain technology in circular supply chains is a hierarchical and interdependent process. The lower levels refer to the basic conditions which affect the higher ones; the higher ones refer to outcomes that become attainable when the underlying technological, organizational, financial and institutional conditions are properly addressed. This hierarchical structure serves as a reference for prioritizing interventions and it goes hand in hand with the causal understanding derived from DEMATEL and the driving–dependence classification derived from MICMAC.

MICMAC Results

In order to get a classification of the 18 factors according to their driving and dependence powers, MICMAC analysis was applied. Based on the results, three groups are identified: Driving, Linkage, and Dependent; with no element of the factors falling under the Autonomous group as shown in Fig. 4.

The Driving group comprises Blockchain infrastructure availability (F6), Top management commitment (F8), Skilled workforce (F9), Organizational digital readiness (F10), Financial investment (F13), Regulatory support (F14), and Environmental sustainability pressure (F17). Among these, Regulatory support (F14) and Environmental sustainability pressure (F17) have the highest driving power of 18 and dependence power of 3, followed by Blockchain infrastructure availability (F6) with driving power 18 and dependence power 4. These factors represent the major foundational drivers of blockchain adoption.

The Linkage group includes Supplier collaboration (F12) and Standardization of data and processes (F15). Their driving/dependence values of 11/9 and 10/9, respectively, indicate that they both influence and are influenced by other factors. Hence, these factors require continuous monitoring and coordinated management.

The Dependent group includes F1, F2, F3, F4, F5, F7, F11, F16, and F18. Product traceability (F1) has the highest dependence power of 15, while Customer awareness and acceptance (F18) has the lowest driving power of 2. These factors are largely outcomes of improvements in infrastructure, organizational readiness, financial resources, collaboration, and regulatory support.

Overall, the MICMAC results indicate that foundational factors should be prioritized before implementation-level outcomes. Strengthening regulatory support, infrastructure, financial investment, management commitment, digital readiness, and workforce capabilities can facilitate improvements in traceability, digital product passports, reverse logistics, remanufacturing, and customer acceptance.

Integrated Interpretation

The integrated DEMATEL–ISM–MICMAC framework shows that blockchain adoption in circular supply chains depends on interconnected

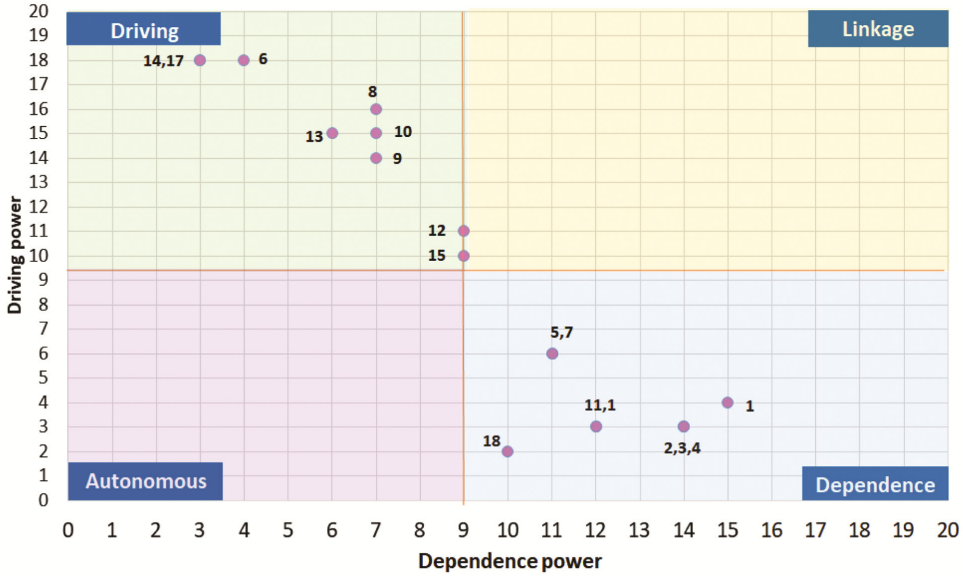


Fig. 4 — MICMAC analysis

technological, organizational, financial, and regulatory factors. Regulatory support, environmental sustainability pressure, and blockchain infrastructure availability emerge as key foundational drivers. Financial investment, top management commitment, digital readiness, and skilled workforce provide the organizational foundation for implementation, while supplier collaboration and data standardization facilitate supply-chain integration. In contrast, product traceability, digital product passports, reverse logistics, remanufacturing certification, and customer acceptance are mainly dependent outcomes. Overall, the findings indicate that blockchain adoption should follow a systematic progression from foundational drivers and organizational capabilities to supply-chain integration and circular outcomes, rather than being treated as an isolated technology initiative.

Managerial and Policy Implications

The results indicate that regulatory support, blockchain infrastructure, financial investment, and top management commitment are important factors that influence the adoption of blockchain. Organizations should then improve their digital readiness, their skilled workforce, and their working relationships with their suppliers, and their data standardization, in order to implement it well. At the policy level, it is necessary to establish regulation, develop infrastructure, standardisation or financial instruments to promote the use of blockchain in circular supply chains. Furthermore, policy should encourage environmental sustainability goals that will facilitate enterprises to implement digital technologies in traceability, digital product passports, reverse logistics, and remanufacturing.

Conclusions

The results reflect the interplay of technology, organization, finances, regulatory, and sustainability components in shaping adoption. Financial investments, management commitment, digital readiness, and workforce capabilities are key support elements for implementing, with regulatory support and environmental sustainability pressure and blockchain infrastructure availability as major foundational drivers. The framework also highlights that the outcomes of the product traceability, digital product passports, reverse logistics, remanufacturing certification and customer acceptance are largely dependent. Therefore, blockchain should not be considered a one-off technological solution, but as a radical change of the system.

One of the major drawbacks of this study is the use of expert judgments that could be subjective and subject to individual perceptions and experiences. The analysis is also confined to the factors identified in the circular supply chain and manufacturing environment, hence the applicability of the key findings is restricted to other sectors or regions. Moreover, DEMATEL-ISM-MICMAC does not statistically investigate the relationships, which are only defined by the structure itself, through large-scale empirical data.

In the future, the fuzzy and uncertainty-based DEMATEL–ISM approaches can be used to cope with ambiguity in expert assessments. Relationships identified can be further explored in an empirical level by using SEM or PLS-SEM. Differences in context can be evaluated by comparative studies across industry and country. In the future, blockchain could be combined with other technologies such as IoT, AI, digital twins and digital product passports to create even more comprehensive frameworks for the transformation of the circular and sustainable supply chain.

References

1 Geissdoerfer M, Savaget P, Bocken N M P & Hultink E J, The circular economy – A new sustainability paradigm?, *J Clean Prod*, **143** (2017) 757–768, doi:10.1016/j.jclepro.2016.12.048.

2 Kirchherr J, Reike D & Hekkert M, Conceptualizing the circular economy: An analysis of 114 definitions, *Resour Conserv Recycl*, **127** (2017) 221–232, doi:10.1016/j.resconrec.2017.09.005

3 Genovese A, Acquaye A A, Figueroa A & Koh S C L, Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications, *Omega*, **66** (2017) 344–357, doi:10.1016/j.omega.2015.05.015.

4 Govindan K & Hasanagic M, A systematic review on drivers, barriers, and practices towards circular economy: A supply chain perspective, *Int J Prod Res*, **56(1–2)** (2018) 278–311, doi:10.1080/00207543.2017.1402141.

5 Saberi S, Kouhizadeh M, Sarkis J & Shen L, Blockchain technology and its relationships to sustainable supply chain management, *Int J Prod Res*, **57(7)** (2019) 2117–2135, doi:10.1080/00207543.2018.1533261.

6 Kouhizadeh M & Sarkis J, Blockchain practices, potentials, and perspectives in greening supply chains, *Sustainability*, **10(10)** (2018) 3652, doi:10.3390/su10103652.

7 Nandi M L, Nandi S, Moya H & Kaynak H, Blockchain technology-enabled supply chain systems and supply chain performance: A resource-based view, *Supply Chain Manag*, **26(6)** (2020) 841–862, doi:10.1108/SCM-12-2019-0444.

8 Kamble S S, Gunasekaran A & Sharma R, Modeling the blockchain enabled traceability in agriculture supply

chain, *Int J Inf Manag*, **52** (2020) 101967, doi:10.1016/j.ijinfomgt.2019.05.023.
9 Govindan K, Mangla S K & Luthra S, Prioritising indicators in improving supply chain performance using fuzzy AHP: Insights from the Indian manufacturing industry, *Int J Prod Res*, **55(12)** (2017) 3501–3520, doi:10.1080/09537287.2017.1309716.
10 Luthra S, Garg D & Haleem A, Identifying and ranking of strategies to implement green supply chain management in Indian manufacturing industry using AHP, *J Ind Eng Manage*, **6(4)** (2013) 930–962, doi:10.3926/jiem.693.
11 Tranfield D, Denyer D & Smart P, Towards a methodology for developing evidence-informed management knowledge by means of systematic review, *Br J Manage*, **14(3)** (2003) 207–222, doi:10.1111/1467-8551.00375.
12 Hsu C C & Sandford B A, The Delphi technique: Making sense of consensus, *Pract Assess Res Eval*, **12(10)** (2007) 1–8, doi:10.7275/pdz9-th90.
13 European Commission, *A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe*, Brussels, Belgium (2020).
14 Christidis K & Devetsikiotis M, Blockchains and smart contracts for the Internet of Things, *IEEE Access*, **4** (2016) 2292–2303.
15 Casino F, Dasaklis T K & Patsakis C, A systematic literature review of blockchain-based applications: Current status, classification and open issues, *Telecommun Syst*, **67**(1) (2018) 55–81.
16 Xu X, Weber I & Staples M, *Architecture for Blockchain Applications*, Springer, Cham (2019).
17 Tornatzky L G & Fleischer M, *The Processes of Technological Innovation*, Lexington Books, Lexington, MA (1990).
18 World Economic Forum, *The Future of Jobs Report 2025*, World Economic Forum, Geneva (2025).
19 Okoli C & Pawlowski S D, The Delphi method as a research tool: An example, design considerations and applications, *Inf Manag*, **42(1)** (2004) 15–29, doi:10.1016/j.im.2003.11.002.
20 Rogers E M, *Diffusion of Innovations*, 5th edn, Free Press, New York (2003).
21 Guide V D R & Van Wassenhove L N, The evolution of closed-loop supply chain research, *Oper Res*, 57**(1)** (2009) 10–18, doi:10.1287/opre.1080.0628.
22 Simatupang T M & Sridharan R, The collaborative supply chain, *Int J Logist Manag*, **13(1)** (2002) 15–30, doi:10.1108/09574090210806333.
23 Joshi M &Nikhade S D, Developing sustainable consumer practices: A framework for managing refurbished electronic goods in India, *J Sci Ind Res*, **83(12)** (2024) 1326–1337, doi:10.56042/jsir.v83i12.9021 .
24 OECD, *Blockchain Policy Series: Blockchain and Emerging Digital Technologies for Enhancing Post-2020 Climate Markets*, OECD Publishing, Paris (2020).
25 Sundin E & Bras B, Making functional sales environmentally and economically beneficial through product remanufacturing, *J Clean Prod*, **13(9)** (2005) 913–925, doi:10.1016/j.jclepro.2004.04.006.
26 Adler M & Ziglio E, Gazing into the Oracle: The Delphi Method and Its Application to Social Policy and Public Health, Jessica Kingsley Publishers, London (1996).
27 Skulmoski G J, Hartman F T & Krahn J, The Delphi method for graduate research, J Inf Technol Educ, **6** (2007) 1–21, doi:10.28945/199.
28 Rowe G & Wright G, Expert opinions in forecasting: The role of the Delphi technique, in *Principles of Forecasting*, edited by J S Armstrong, Springer, Boston (2001) 125–144, doi:10.1007/978-0-306-47630-3_7.
29 Palinkas L A, Horwitz S M, Green C A, Wisdom J P, Duan N & Hoagwood K, Purposeful sampling for qualitative data collection and analysis in mixed method implementation research, *Adm Policy Ment Health*, **42(5)** (2015) 533–544, doi:10.1007/s10488-013-0528-y.
30 Joshi M, Mankar R & Shukla H, Identification and evaluation of factors influencing software quality using Pythagorean fuzzy DEMATEL approach, *Int J Next Gener Comput*, **13(5)** (2022).
31 Joshi M, Prioritizing agility factors in IT-enabled healthcare supply chain under uncertainty: A joint ISM–MICMAC approach, *J Sci Ind Res*, **83(1)** (2024) 67–75, doi:10.56042/jsir.v83i1.4452.