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Empirical analysis of barriers to implement Blockchain Technology in manufacturing environment: A developing economy perspective

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Table 9: Interpretive matrix

Notation	BB1	BB2	BB3	BB4	BB5	BB6	BB7	BB8	BB9	BB10	BB11
BB1	-	0	0	0	Resistance to technical silos make poor infrastructure	0	0	0	0	0	0
BB2	0	-	0	0	0	0	0	0	0	0	0
BB3	Issue with transparency hinder technical silos	Issue with transparency hinder collaboration	-	0	0	Issue with transparency hinder willingness to adopt blockchain	0	0	0	Issue with transpare ncy hind er regulat ory	Issue with information sharing cause technical infeasibility
BB4	0	0	Lack of awareness create issues with transparency	-	0	Lack of awareness hinder willingness to adopt blockchain	Lack of awareness hinder innovation	Lack of awareness hinder ease of protocols selection	0	0	Lack of awareness hi nder technologica l knowledge
BB5	0	0	0	0	-	Poor infrastructur e hinder willingness to adoption	0	0	Poor system makes process complex	0	0
BB6	0	Poor management involvement hinder collaboration	0	0	0	-	0	0	0	0	0
BB7	0	Lack of training hinder collaboration	Lack of training increase issues with	0	0	0	-	Lack of training increase complication	0	0	Lack of training increase technologic

			transparency					of protocols selection			al infeasibility
BB8	Complicated protocols hinder technical silos	0	0	0	0	Complicated protocols resistance to blockchain adoption	0	-	0	Complicated protocol hinder regulatory	Technical infeasibility hinder protocol selection
BB9	0	0	0	0	Costly setup hinder willingness	Poor system makes process complex	0	0	-	0	0
BB10	Unclear regulatory resistance to technical	0	0	0	0	Unclear regulatory hinder willingness to adoption	0	0	Unclear regulatory make system complex and costly	-	0
BB11	Technology infeasibilities resistance to create technical silos	0	Issue with information sharing cause technical infeasibility	0	0	Technological infeasibilities hinder willingness to adoption	0	Technical infeasibility hinder protocol selection	0	0	-

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Abstract

Purpose: The present study aims to identify the critical barriers of Blockchain Technology (BT) implementation in a manufacturing environment in context of developing countries.

Design/Approach/Methodology: In the present work, barriers of BT adoption has been investigated via literature review and screened them through expert's input. Further, the interrelationship among screened barriers were framed using a modified Total Interpretive Structural Modelling (mTISM) and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) approach. The mTISM aims to develop a contextual relationship-based performance model with the logic behind transitive links formation to explore the dominant barriers. The MICMAC approach categorizes the Blockchain adoption barriers based on their driving and dependence power.

Finding: Based on the analysis, nine barriers of BT adoption in manufacturing environment were identified and finalized through statistically. The obtained results exhibit that lack of awareness about Blockchain and poor training/human expertise on innovative technologies are the most critical barriers that hinder Blockchain adoption. This study provides a roadmap and may facilitate manufacturing professional, consultant, governing bodies, and policymakers in the preparation of active strategies to overcome challenges in adoption of BT in the running system.

Originality: Literature is full with analysis of barriers of BT adoption in the domain of supply chain, operation management, and manufacturing in context of developed nation only. The present work is the first attempt to examine the BT adoption barriers in the manufacturing environment of developing economy and covered the mutual-interrelationship among them via modified TISM approach.

Keywords: Blockchain; Manufacturing Industries; Barriers; Modified Total Interpretive Structural Modelling; MICMAC.

1. Introduction

Due to the unpredictable nature of market economics and consumer demand, manufacturing organisations are much more focused on producing good quality products at low-cost (Garza-Reyes *et al.*, 2016). The demand for competitive products is responsible for extra pressure on manufacturing industries to perform with lower operating capital to sustain in global market (Jirasukprasert *et al.*, 2015). Therefore, manufacturing industries is on the cusp of revolutionary growth by integrating the physical world with virtual concept. In fourth industrial revolution, it is essential to adopt digitalization, intelligent protocols, along with automation within the manufacturing facility (Senna *et al.*, 2019). The adoption of digitalization within production facilities must be incorporated without affecting its impact on customers and environment (Trappey *et al.*, 2017). Digitalization and automation are expected to be realised by amalgamation of various emerging technologies like Internet of Things (IoTs), big data, machine learning, Blockchain, Cyber-Physical System (CPS), radio-frequency identification (RFID), smart sensors, cloud-computing, Artificial Intelligence (AI), 3D printing etc. (Bag *et al.*, 2021). The automation and digitization empowers the rapid flow of data, products, and appliances through highly secured and trustworthy channels (Zamil *et al.*, 2020). Proper exploration of data and information related to all manufacturing activities is one of the major key aspects for digital transformation in manufacturing facilities (Al Adwan *et al.*, 2021) (Dagnaw, 2020). Still, manufacturing units are relying on centralized systems to gather, manage and store the informative data that is not real-time capable and vulnerable to fraud and attacks in many ways.

Blockchain is the technology that has evident potential of decentralization, immutability, distributed consensus and transparency for manufacturing systems (Swan, 2015) (Wang, Singgih, *et al.*, 2019). The factory systems can be connected with Blockchain platform to enable automation in value chain and provide better understanding of production systems, improve quality, and risk management (Chang *et al.*, 2019). Blockchain technology gains popularity especially in supply chain (SC) at global level due to its extended benefits and feasible application within their existing infrastructures (Risso *et al.*, 2023) (Han and Fang, 2024). The managers can take smart decisions regarding successful adoption of Blockchain if the relationship among barriers is analyzed thoroughly (Mathivathanan *et al.*, 2021). Although the literature provides significant insights on quantitative analysis of barriers, but most of studies are related to green SC (Kouhizadeh and Sarkis, 2019), sustainable SC (Kouhizadeh *et al.*, 2021), agriculture SC (Yadav *et al.*, 2020), banking sector (Saheb and Mamaghani, 2021), service sector (Biswas and Gupta, 2019), maritime SC (Balci and Surucu-Balci, 2021) etc. But no studies are there in literature that expresses the mutual relationship among barriers to adoption of Blockchain in manufacturing setting in context of developing countries like India. The application of Blockchain in manufacturing industries of developing economies are at infancy stage and consists numerous hinders in actual implementation (Pal, 2021). Therefore, the present study intensions to fill this gap through proposing a model of identified eleven barriers of Blockchain adoption in manufacturing industries. Modelling the identified barriers is crucial for adopting Blockchain technology in manufacturing settings because it reveals the connections between different barriers at various levels, which is a complex task. Therefore, it is essential to use a robust technique to effectively model the interactions among Blockchain barriers and estimate the optimal solution. In this context, Modified Total Interpretive Structural Modelling (mTISM) is used to modelled the barriers of Blockchain which leads to high gain in manufacturing environment. The mTISM offers several key advantages over TISM, including enhanced interpretative depth, improved methodological rigor, better decision-making support, greater flexibility, enhanced stakeholder collaboration, and increased transparency (Dhir and Dhir, 2020). Also, the mTISM approach particularly valuable for analyzing complex systems where relationships and contextual depth are critical. Thus, in the present study, the barriers of Blockchain are modelled through mTISM approach with the help of industrial expert's input. In this context, the authors have set the following research questions, which explore through the present study:

RQ1: What are the barriers to the adoption of Blockchain in manufacturing environment?

RQ2: What are the contextual relationships and interactions among the barriers?

RQ3: What are the implications of the barriers to adoption of Blockchain technology in manufacturing setting of developing countries?

This study theoretically contributes by identifying and modelling the Blockchain barriers that may create hurdle for the manufacturing sector to move towards digitization. This will facilitate the managers, researchers, professional consultant, governing bodies, and policymakers in the preparation of active strategies to overcome them and successfully implement Blockchain technology.

The remaining sections of this manuscript are organized as follows: Section 2 explores the connect between Blockchain and manufacturing industries and identify the barriers to adopt Blockchain technology. Section 3 exhibits the research methodology adopted to conduct this study. Section 4 presents the detailed steps of mTISM approach to develop the model of barriers and highlights the barriers as per their driving and dependence power using MICMAC analysis. Section 5 summaries the discussion on findings followed by theoretical and managerial implications explained in Section 6. Section 7 presents the conclusion of study with limitation of present study and future research direction.

2. Literature Review

To conduct the literature review, a systematic literature review approach was used in this research. As per this approach, 134 articles were downloaded using keywords blockchain in manufacturing, blockchain's barriers; Modified Total Interpretive Structural Modelling. The popular publishers such as Scopus, Web of Science, Emerald Insight, IEEE Xplore, Taylor & Francis, Springer, and Elsevier are selected as search engine for literature. Moreover, the downloaded articles were examined to be published in English language only and belongs to journals and results, 65 articles out of 134 were finalized. These articles have been analyzed comprehensively to explore the significant research gap. The content analysis reveals that the manufacturing industries are showing their interest in adoption of Industry 4.0 techniques for widening globally. The wide-ranging adoption of digitalization and automation enables the competitiveness and growth by boosting productivity and revenue of manufacturing sectors (Attaran, 2021).

Blockchain technology with specific properties showing promising growth and has been offered as the future of manufacturing sectors with potential benefits (Leng *et al.*, 2021). The World Economic Forum (World Economic Forum, 2015) envisages that the Blockchain as an emerging technology will be among top contributor 'mega-trends' which is probably to shape the globe in coming decade. It is the foundation for decentralized and distributed ledger that proffers a transparent and immutable mechanism for adding transactions in both industry and business (Vatankhah Barenji *et al.*, 2019). Blockchain signifies a distributed ledger that is stored after validation and verification in form of block on network nodes. The association and communication happen among geographically distributed participants in peer-to-peer network through verified transactions called ledger and it is publicly available to all participants. As the Blockchain works in decentralized manner, the association among participants has accomplished based on present ledger and the validated transactions have added to the next block. The mechanism of consensus employment is achieved using various consensus algorithms like Proof-of-Stack, Proof-of-work, Proof-of-Burn, Proof-of-Authority and Practical Byzantine Fault Tolerance etc. The selection of consensus mechanism is totally depends on nature of Blockchain leads to instigation factors of Blockchain in manufacturing industries (Feng *et al.*, 2020) (Shi and Guo, 2020) as shows in Table 1.

Table 1: Blockchain features suitable for manufacturing industry (Angrish *et al.*, 2018) (Singh *et al.*, 2024)

Blockchain features	Instigation factors of the Blockchain	Blockchain in Manufacturing
Immutability	Cryptographic measures	Immutability leads to improved auditability as all the available information is unalterable and secured, it plays major role for potential legal disputes E-based data instead of paper-based transactions gives promising results in terms of security Save resources and decrease consumption of resources
Transparency	Real-time transaction generation with full history records and redundancy	Real time tracing offers promising improvement in transparency for all participants Autonomous access of record enhance agility The risk of one point of failure is totally abolished with decentralization
Disintermediation	Decentralization that eradicates central authority	Peer to per exchange of information reduce overall cost Equality among partners and least dependency
Inevitable	Consensus of transaction, and Cryptographic measures	Consensus mechanism to reduce opportunism Transactions are validated and verified legally
Automation	Smart contract	Data and payments are automatically transfer leads to cost reduction

From literature survey, it has been concluded that the adoption of Blockchain within manufacturing industry enables numerous potential benefits as decentralization, reliability, smart contract, transparency (Ko *et al.*, 2018) (Karamchandani *et al.*, 2021) (Benzidia *et al.*, 2021). These potential benefits facilitate solving issues faced by manufacturing sectors as discussed in Table 2. The alteration of available data and information can be controlled using Blockchain because before alteration each participant needs to verify and validate the made changes (Idrees *et al.*, 2021). The ledger is publicly available to all participants and required permission for prior changes. Also, in conventional manufacturing system, there is lack of real-time based data and information about operation and process (Laabs and Dukanović, 2021) (Raja Santhi and Muthuswamy, 2022). Blockchain adoption enables the participants to track and trace the processing of operations in real time (Westerkamp *et al.*, 2020). In conventional manufacturing, systems are centralized in nature where data or crucial information can be altered without knowledge (Ahmad *et al.*, 2022). Also, lack of detailed description about processes and operation causes delay in production and transformation. Table 2 exhibits the problem in conventional manufacturing systems and potential of Blockchain to solve such issues in manufacturing.

Table 2: Potential of Blockchain in manufacturing (Leng *et al.*, 2021)

<table>
<tr><th>Problems in conventional manufacturing</th><th colspan="2">Potential of Blockchain implementation in manufacturing</th></tr>
<tr><td rowspan="3">• The system is centralized where the information can be altered without prior knowledge
• Participants may be fraud or dishonest
• Lack of detailed description of operation/raw material
• Delay in material transformation
• Information gaps can lead to inefficiencies
• The planned schedule of process cannot be performed precisely</td><td>Embellished collaboration</td><td>• Decentralization
• Security and privacy of information among participants
• All participants have information of ledger
• Sovereignty
• All participants need to validates the new transaction
• Transparency</td></tr>
<tr><td>Smart contract</td><td>• Enhance efficiency
• Connection with token</td></tr>
<tr><td>Business models</td><td>• Centralized to distributed system
• Communication among participants
• Enhance productivity
• Overall production reduction</td></tr>
</table>

2.1 Identification of Barriers of Blockchain in manufacturing industry

Although the industries are flattering more awareness and informed, but the role of digitization and automation in adding value as well as numerous benefits to manufacturing sectors are not fully recognized (Wang *et al.*, 2021). Reaping the potential and benefits of Blockchain in industries is not conceivable without knowing the suitable execution procedure, which needs a through preadoption analysis, including all possible barriers and challenges identification (Vafadarnikjoo *et al.*, 2021) (Lohmer and Lasch, 2020). Thus, the investigation of the barriers is done through literature, which explored by using various keywords like ‘Failure Factor’, ‘Obstructions’, ‘Barriers’, ‘Challenges’, ‘Blockchain’, ‘Manufacturing Industry’. Thereafter, a questionnaire was framed for collecting the expert’s viewpoint about the identified barriers of Blockchain in manufacturing setting. These experts belong from manufacturing industries and academia background. Before sending the questionnaire to experts for data collections, content validity index was estimated and obtained 0.88 which seems that questionnaire content is valid and satisfactory. Thereafter, the data was collected by adopting convenience sampling technique. This technique is non-probability in nature and was used by numerous researchers for collecting available source of information from people. Table 3 demonstrates a summary of barriers identified from the literature.

Table 3: List of barriers to adoption of Blockchain in manufacturing sector

Notation	Barriers	Description	Literature support
BB 1	Resistance to create individual technical silos	Blockchain permits the closure of technical silos by providing isolated and one-off solution. But management is not ready to create individual storage for technical and informational silos.	(Idrees *et al.*, 2021) (Wang, Singgih, *et al.*, 2019)
BB 2	Concerns with collaboration and network formation	Due to lack of appropriate knowledge and clarification about Blockchain technology, industries are avoiding collaboration and network formation.	(Cole *et al.*, 2019)(Hackius and Petersen, 2020)
BB 3	Issues with the transparency and revelation of "crucial information"	Management hesitates to share crucial information to individual in real-time, therefore issues with transparency of information cause blocking point.	(Saberi *et al.*, 2019)(Kamble *et al.*, 2019)(Wang, Han, *et al.*, 2019)
BB 4	Lack of awareness about Blockchain	Lack of awareness and knowledge and infancy of Blockchain hinders the advantages of Blockchain adoption within firm.	(Kurpjuweit *et al.*, 2021)(Kamble *et al.*, 2019)
BB 5	Poor supportive infrastructure	Poor supportive infrastructure hinders the adoption of Blockchain within firm.	(Idrees *et al.*, 2021) (Makhdoom *et al.*, 2019) (Mougayar, 2016)(Babich and Hilary, 2020)
BB 6	Poor involvement of top management	Poor involvement support of top management is most crucial factor that affects any strategic decision related to technology adoption.	(Babich and Hilary, 2020)(Hackius and Petersen, 2020)
BB 7	Lack of training/human expertise on innovative	Lack of training/human expertise on innovative technology hinders the adoption of technology within the firm.	(Saberi *et al.*, 2019)(Biswas and Gupta, 2019)

	technology		
BB 8	Complicated process of protocols selection	The complicated process of protocols selection discourages the management to adopt Blockchain.	(Makhdoom *et al.*, 2019) (Lacity and Khan, 2019)
BB 9	Complex and costly setup	The complexity, massive financial investment, software requirement, initiator commitment and costly setup resist management for Blockchain adoption.	(Kamble *et al.*, 2019)(Saberi *et al.*, 2019)(Wang, Han, *et al.*, 2019)
BB 10	Unclear regulatory	Management is somehow unwilling due to unclear regulatory about Blockchain.	(Kurpjuweit *et al.*, 2021)
BB 11	Technological infeasibility	Technological infeasibility, lack of computing power and maturity level hinders the Blockchain adoption within firm.	(Lacity and Khan, 2019)(Kayikci *et al.*, 2022)

3. Research Methodology

This section presents the research methodology adopted for analysis of barriers to adoption of Blockchain in manufacturing sector through mTISM approach to construct contextual relationship-based model. Further, it followed by MICMAC analysis to cluster the barriers based on their driving and dependence power. The steps involved in mTISM approach was taken from (Jayalakshmi and Pramod, 2015) and barriers are categorised in four quadrants as driver, dependent, linkage, and autonomous by using MICMAC analysis. Figure 1 exhibits the comprehensive procedure used to conduct the present study.

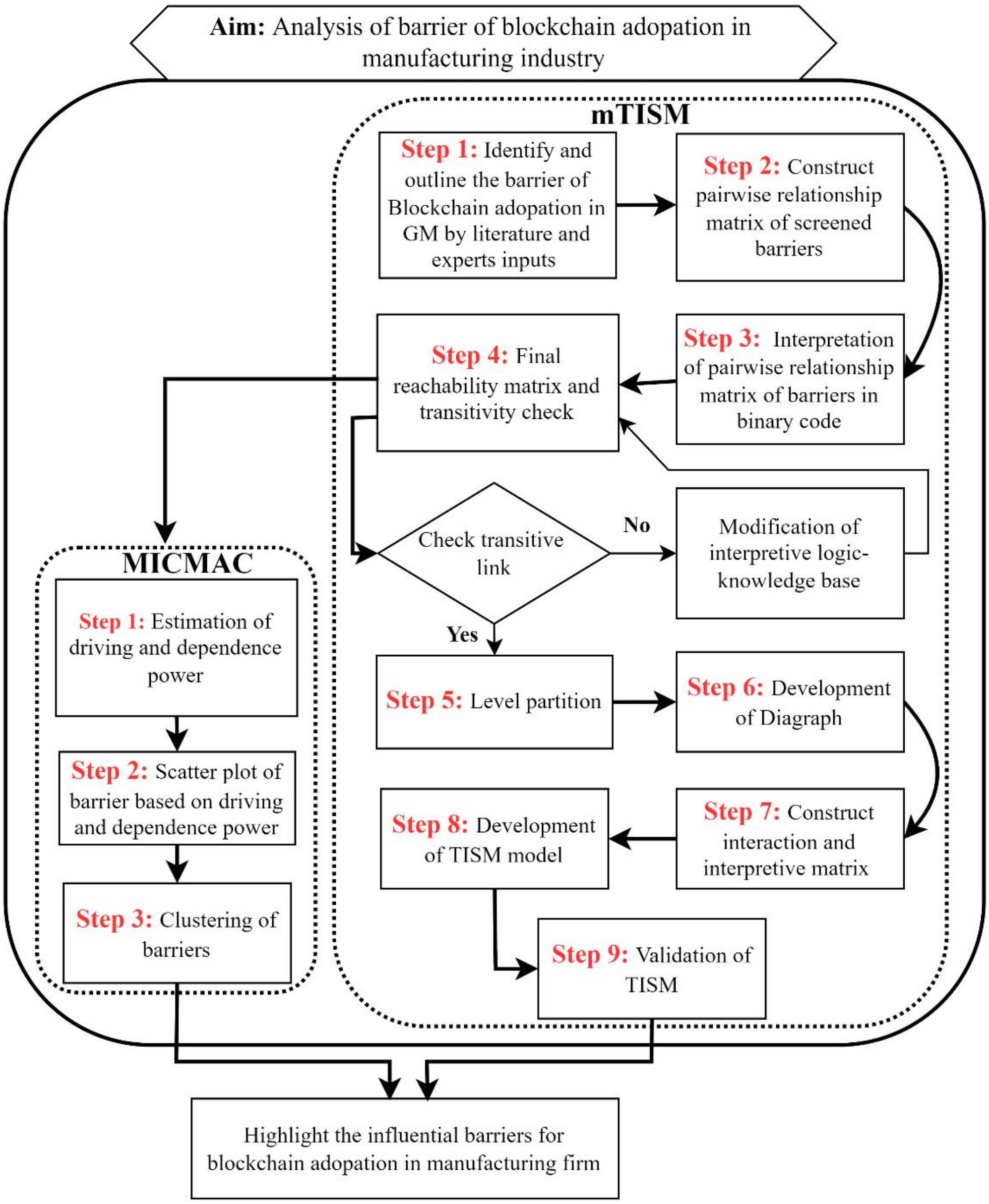

Figure 1: Adopted research methodology

In the first step of adopted methodology, the barriers of Blockchain have been identified via systematic literature review and further validated them via expert's input. The selection of experts has been done using purposive sampling technique and their views were collected through questionnaire survey. Moreover, the collected responses have been analyzed via statistical tools. The statistical analysis provides a list of final barriers which are further modelled by the mTISM approach. This method was adopted because the developed model describes the transitive link among barriers with their reason behind linkage of interpretive structural modelling (ISM) (Jayalakshmi and Pramod, 2015). It is an advance approach that overcome the pitfall of total ISM method through retracing the transitive link among barriers. In total ISM, let suppose factor A influences factor B and other side, factor A and C have transitive relationship, then factor B directly effects factor C as per law of transitivity. But, in mTISM, the actual reason for the transitivity if any between barriers are checked through knowledge-based assessment from expert input and only the effective transitive link considered for development of model (Sindhwani and Malhotra, 2017). Thereafter, ineffective transitive links are omitted and only real transitive links are considered during model development. The developed model in mTISM is known as diagraph where the directions of relationship among barriers are displayed with the help of arrow (Shibin *et al.*, 2017). The level of diagraph provides the influential barriers with their contextual relationship defined through arrow. Overall, the mTISM model portrays only the significant links and hence provides a more trust-worthy investigation among the barriers.

Moreover, the barriers are clustered through MICMAC (Matriced'Impacts Croises-Multipication Applique' and Classment). The relationship between the barriers revealed in the TISM model is never equal; certain barriers might be strong while others might be weak (Krishnan *et al.*, 2021). The stronger relationship facilitates the success of model in better way. Based on the strength of power (driving power) and mutual dependence among each barrier, MICMAC analysis categories the barriers and identifies the key barriers that hindered the system. Finally, to validate the formed mTISM model, the expert's input is considered and analysed statistically which provides accepted model. The steps involved in mTISM and MICMAC analysis is explained in the next section.

4. Application of proposed methodology

In this section, the progressive steps of mTISM approach are explained with collected data for identifying the influential barriers for Blockchain adoption in manufacturing sector. Also, the validation of mTISM model outlines with the help of expert's input.

4.1 Steps of mTISM approach

4.1.1 Step 1. Identify and outline the barriers

In the first step, we identify the critical barriers to adoption of Blockchain in manufacturing environment in context of developing countries. In our case, total eleven potential barriers are identified from literature including Resistance to create individual technical silos (BB1), Concerns with collaboration and network formation (BB2), Issues with the transparency and revelation of "crucial information" (BB3), Lack of awareness about Blockchain (BB4), Poor supportive infrastructure (BB5), Poor involvement of top management (BB6), Lack of training/human expertise on innovative technology (BB7), Complicated process of protocols selection (BB8), Complex and costly setup (BB9), Unclear regulatory (BB10), and Technological infeasibility (BB11) are put into interpretive knowledge-based for getting the experts input.

This study is based on qualitative approach; thus, we are required the responses of 110 paired relationship-based questions with their reasons of relationship. For the experts and our entire study, this took a lot of time. Therefore, we decided to focus primarily on a small number of seasoned professionals who are expertise in the application of Industry 4.0 in manufacturing sector and have dealt with several smart projects in their respective enterprises over the years. These experts were either general managers or head of manufacturing organizations and are decision makers having authorities to approve any changes required at their organizations.

In this study, we have targeted to experts from those industries who have won the title of "India Manufacturing Excellence Award 2021". A total of ten experts (seven from industry and three from academic) were provided the exploitable responses on pairwise relationship of barriers. The industrial experts are having average ten plus years of experience and academic experts are belongs from top engineering and management universities of India with best knowledge of Blockchain. The in-depth awareness on Blockchain and its barriers in manufacturing industries was given to the selected ten experts through brainstorm session followed by personal interviews. At this stage, a detail explanation of eleven barriers was provided by experts and thus, these experts were found most suitable for our mTISM model.

4.1.2 Step 2. Construct pairwise relationship matrix

In this step, the contextual relationship between each barrier is formed with the help of expert's opinion. The detail interpretation is provided during formation of contextual relationship matrix, i.e., if barrier BB1 will influences the barrier BB2, then answer is provided in YES/NO term. If response is in YES, then the reason/logic how or in what way the barrier BB1 will influences barrier BB2, also recorded in the knowledge base matrix. Here the experts are needs to provide the contextual relationship among all barriers, which further explored in knowledge base matrix. In this study, as we consider a total of eleven barriers, so total row in knowledge base table is 11*10=110. All these 110 likely relationships were presented in front of experts and based on received responses, the knowledge base matrix was formed as shown in Table 4. Only the positive responses like more than 50% 'YES' answer about any relation, were considered for further comparative analysis, otherwise it was given as 'NO'.

Table 4: The knowledge base matrix of contextual relationship among barriers

Sr. No.	Barrier notation during comparison	Paired comparison of barriers	Contextual relationship existing (YES/NO)	In what way a barrier will influence/enhance other barrier? Give reason in brief
1	BB1-BB2	Resistance to create individual technical silos will influence Concerns with collaboration and network formation	No	
2	BB2-BB1	Concerns with collaboration and network formation will influence Resistance to create individual technical silos	No	
3	BB1-BB3	Resistance to create individual technical silos will influence Issues with the transparency and revelation of "crucial information"	No	
4	BB3-BB1	Issues with the transparency and revelation of "crucial information" will influence Resistance to create individual technical silos	Yes	Poor transparency of information leads to create resistance in technical silos.
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
109	BB11-BB9	Technological infeasibility will influence Complex and costly setup.	No	
110	BB11-BB10	Technological infeasibility will influence Unclear regulatory.	No	

4.1.3 Step 3. Convert pairwise relationship matrix into binary code

Based on the received knowledge base table, the logic behind YES/NO relationship are compared and formed an initial reachability matrix as shown in Table 6. For each (i,j) cell, there are only entries of two digits either '1' or '0', where '1' stands for the presence of influential relationship of B_i over B_j and '0' stands for absence of influential relationship (Jayalakshmi and Pramod, 2015). During comparison of relationship between barriers, '1' is directly assigned to diagonal cell and remaining cells consist either '1' or '0' binary code. In the formed initial reachability matrix (Table 5), the cells consisting '1' are reflecting the direct relationship and highlighted in blue, whereas, diagonally always assigned '1' and highlighted in pink (Dubey *et al.*, 2015).

Table 5: Initial reachability matrix

Barrier	Notation	BB1	BB2	BB3	BB4	BB5	BB6	BB7	BB8	BB9	BB10	BB11
Resistance to create individual technical silos	BB1	1	0	0	0	1	0	0	0	0	0	0
Concerns with collaboration and network formation	BB2	0	1	0	0	0	0	0	0	0	0	0
Issues with the transparency and revelation of "crucial information"	BB3	0	0	1	0	0	1	0	0	0	1	1
Lack of awareness about Blockchain	BB4	0	0	1	1	0	1	1	0	0	0	1
Poor supportive infrastructure	BB5	0	0	0	0	1	1	0	0	1	0	0
Poor involvement of top management	BB6	0	1	0	0	0	1	0	0	0	0	0
Lack of training/human expertise on innovative technology	BB7	0	0	0	0	0	0	1	1	0	0	1
Complicated process of protocols selection	BB8	0	0	0	0	0	1	0	1	0	1	1
Complex and costly setup	BB9	0	0	0	0	1	1	0	0	1	0	0
Unclear regulatory	BB10	0	0	0	0	0	1	0	0	0	1	0
Technological infeasibility	BB11	0	0	1	0	0	0	0	1	0	0	1

4.1.4 Step 4. Final reachability matrix

In this step, the initial reachability matrix is converted in to final reachability matrix by considering the transitivity among barriers if any based on the transitivity rule. As per this rule, if barrier BB1 influences BB3 and BB3 influences BB5, then BB1 influences BB5 (Yadav and Desai, 2017). The interpretation is required to be fill with one or more barriers those are forming transitivity among barriers significantly. For example, the transitivity relation exists between the barriers BB4 (Lack of awareness about Blockchain) and BB8 (Complicated process of protocols selection). The initial reachability matrix was not shown any relation, but the TISM recommends that the lack of awareness about Blockchain in firms makes the process for them more complex to selection the protocols, which indirectly impact the Blockchain adoption. Only those transitive relationship are considered, which having significant interpretation, and remaining were ignored for further analysis (Jayalakshmi and Pramod, 2015). There are many indirect relationships found during transitivity check and shown them in final reachability matrix as Table 6. The transitive link between barriers is shown in green and noted the corresponding elements, which provided the transitivity. The same transitive link was discussed with experts and their inputs were recorded in interpretation column; results the ineffective transitive links were ignored based on expert's opinion. This is the prime upgrades that a mTISM model offers.

Table 6: Final reachability matrix

Barrier	Notation	BB1	BB2	BB3	BB4	BB5	BB6	BB7	BB8	BB9	BB10	BB11
Resistance to create individual technical silos	BB1	1	0	0	0	1	0	0	0	1	0	0
Concerns with collaboration and network formation	BB2	0	1	0	0	0	0	0	0	1	0	0
Issues with the transparency and revelation of "crucial information"	BB3	1	1	1	0	0	1	0	0	0	1	1
Lack of awareness about Blockchain	BB4	0	0	1	1	0	1	1	1	0	0	1
Poor supportive infrastructure	BB5	0	0	0	0	1	1	0	0	1	0	0
Poor involvement of top management	BB6	0	1	0	0	0	1	0	0	0	0	0
Lack of training/human expertise on innovative technology	BB7	0	1	1	0	0	0	1	1	1	0	1
Complicated process of protocols	BB8	1	0	0	0	0	1	0	1	0	1	1

selection												
Complex and costly setup	BB9	1	0	1	0	1	1	0	0	1	0	0
Unclear regulatory	BB10	1	1	0	0	1	1	0	0	0	1	0
Technological infeasibility	BB11	1	0	1	0	1	1	0	1	0	0	1

4.1.5 Step 5. Level partition

In this step, the level is being assigned to each barrier based on the reachability set, antecedent set and intersection set through the similar way as in ISM approach. The reachability set for a specific barrier is the factor itself and other factors that the specific barrier helped to attain (Attri *et al.*, 2020). The antecedent set for a specific barrier is the factor itself and other factors that contributed to achieving it (Khaba and Bhar, 2018). The intersection set for reachability and antecedent sets have also been estimated to partition the final reachability matrix. The barriers which consist same reachability set and intersection set, are assigned in same and top level in diagraph and mTISM model. Thereafter, level 1 barriers were eliminated from the entire set during next iteration. The iteration is continued until each barrier is allotted in their corresponding levels. All barriers are assigned in particular levels as shown in Table 7.

Table 7: Level partitions of barriers

Barrier	Reachability set	Antecedent set	Intersection set	Level
BB1	1,10	1,3,4,7,8,10,11	1,10	III
BB2	2,6	1,2,3,4,5,6,7,8,9,10,11	2,6	I
BB3	3,8,11	3,4,7,8,11	3,8,11	IV
BB4	4,7	4,7	4,7	V
BB5	5,9	1,3,4,5,7,8,9,10,11	5,9	II
BB6	2,6	1,2,3,4,5,6,7,8,9,10,11	2,6	I
BB7	4,7	4,7	4,7	V
BB8	3,8,11	3,4,7,8,11	3,8,11	IV
BB9	5,9	1,3,4,5,7,8,9,10,11	5,9	II
BB10	1,10	1,3,4,7,8,10,11	1,10	III
BB11	3,8,11	3,4,7,8,11	3,8,11	IV

4.1.6 Step 6. Development of diagraph

The diagraph is the graphical representation of barriers and links among barriers are shown through arrow based on the level assigned them (Jayalakshmi and Pramod, 2015). Firstly, the direct links among barriers are shown through continuous arcs, and the effective transitive links are expressed with the help of dashed arcs (Sindhwani and Malhotra, 2017). In the present study, the diagraph of eleven barriers is developed based on their level partition and links are exhibited based on relationships in the final reachability matrix. Figure 2 is representing the diagraph developed through continuous arcs and dashed arcs used for direct links and transitive links, respectively. The barriers influences each other which are lies at same level and thus, connected with the bidirectional arrows among the same (Sushil, 2018).

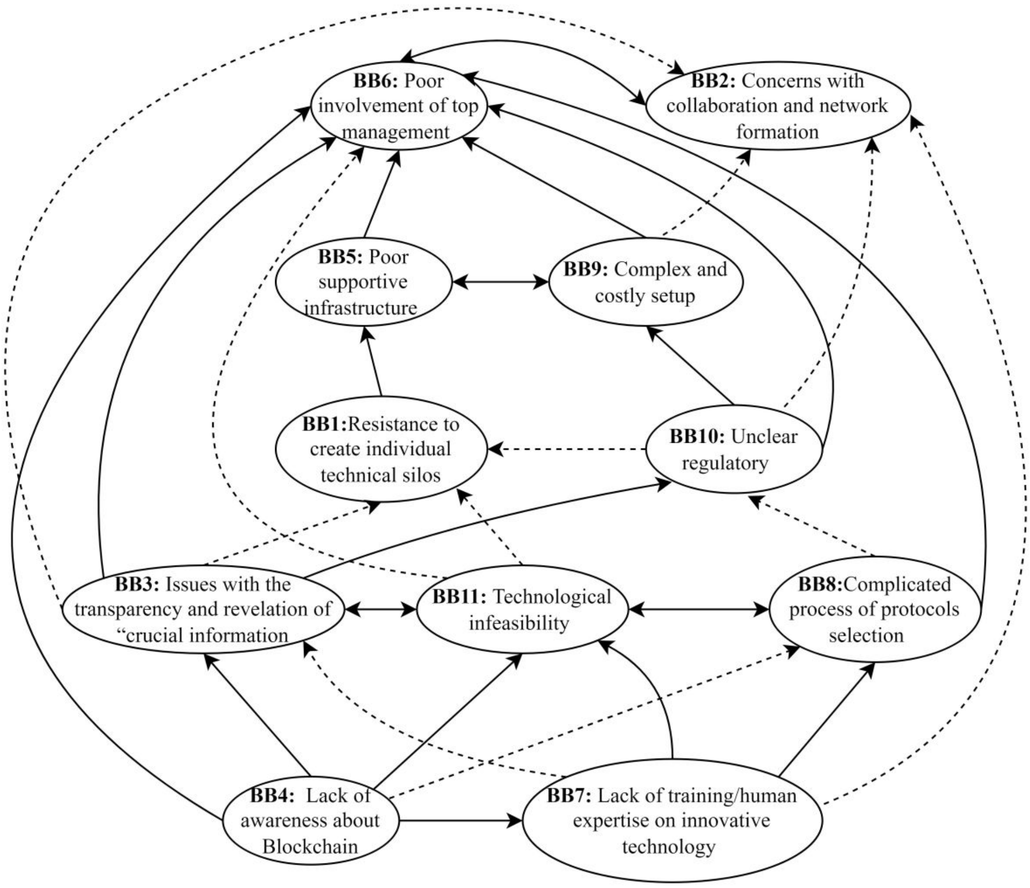

Figure 2: Diagraph of barriers (mTISM model)

4.1.7 Step 7. Interaction and interpretive matrix

On the basis of obtained diagraph, a binary interaction matrix is formulated by replacing the direct interactions with entry '1' and the remaining cells are void of entry (Mathivathanan *et al.*, 2021). The knowledge base matrix provides the effective transitive links, which also represented with entry '1*'. In the present case, a 11×11 interpretive matrix was developed with entries from the logic knowledge base for the cells with value '1'. The interaction matrix and interpretive matrix are shown in Table 8 and Table 9, respectively.

Table 8: Interaction matrix

Barrier	Notation	BB1	BB2	BB3	BB4	BB5	BB6	BB7	BB8	BB9	BB10	BB11
Resistance to create individual technical silos	BB1	-	0	0	0	1	0	0	0	0	0	0
Concerns with collaboration and network formation	BB2	0	-	0	0	0	0	0	0	0	0	0
Issues with the transparency and revelation of "crucial information"	BB3	1*	1*	-	0	0	1	0	0	0	1	1
Lack of awareness about Blockchain	BB4	0	0	1	-	0	1	1	1*	0	0	1
Poor supportive infrastructure	BB5	0	0	0	0	-	1	0	0	1	0	0
Poor involvement of top management	BB6	0	1	0	0	0	-	0	0	0	0	0
Lack of training/human expertise on innovative technology	BB7	0	1*	1*	0	0	0	-	1	0	0	1
Complicated process of protocols selection	BB8	1*	0	0	0	0	1	0	-	0	0	1
Complex and costly setup	BB9	0	0	0	0	1	1	0	0	-	0	0
Unclear regulatory	BB10	1*	0	0	0	0	1	0	0	1	-	0
Technological infeasibility	BB11	1*	0	1	0	0	1*	0	1	0	0	-

Table 9: Interpretive matrix (refer Appendix A)

4.1.8 Step 8. Development of mTISM model

In this step, the information from interpretive matrix is depicted in the form of respective links in the constructed diagraph (Jayalakshmi and Pramod, 2015). This step is developed the final mTISM model with suitable reason of transitive links as shown in Figure 3.

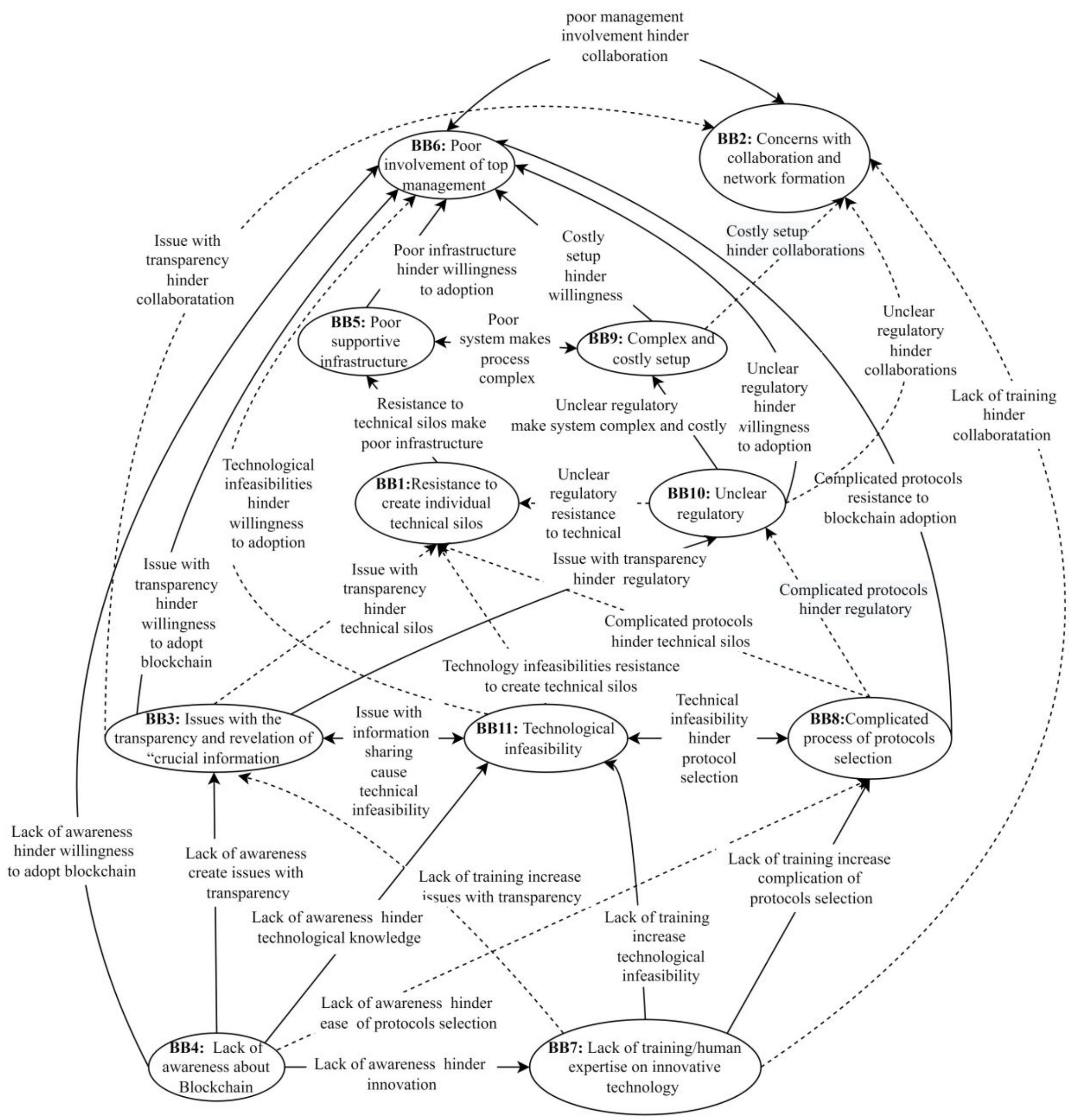

Figure 3: Modified Total Interpretive Structural Model (mTISM)

4.1.9 Step 9. Validation of mTISM

In the present case, the developed mTISM model consists involvement of limited number of experts because of formation of 110 pairwise comparison matrix with their interpretive logic. The formation of 110 pairwise comparison matrix requires huge time and also tough to maintain synchronization among response processes of experts. Therefore, we were considered only ten experts who agreed to provide their suggestion in model development. After reduction in number of links, the developed mTISM model has 30 significant links which makes much easier for any experts to validate the links. The same group of experts can be used to assess the developed model through validating the links as suggested by (Jayalakshmi and Pramod, 2015). Therefore, a Likert scale of '1' to '5' where 1 stand for strongly disagree and 5 stands for strongly agree was used to collect the expert's response. The link in model is accepted if it consists an average score of 3 or more and same score is applicable for accepting the entire model (Jayalakshmi and Pramod, 2015). The obtained responses from experts related to link validity is shown in Table 10, which exhibit the overall score more than 3 and hence we can accept the model. The final validated mTISM model is shown in Figure 4.

Table 10: Assessment of mTISM model

SN	Derived relationship	Expert's responses										Average response	Accept/Reject link
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10		
1	Lack of Blockchain awareness hinder innovation	4	5	3	4	4	5	5	3	3	3	3.9	Accept
2	Lack of awareness hinder ease of protocols selection	5	4	5	3	3	4	4	5	5	5	4.3	Accept
3	Lack of awareness hinder technological knowledge	3	5	4	5	5	3	3	5	5	4	4.2	Accept
4	Lack of awareness hinder willingness to adopt Blockchain	5	3	5	4	4	3	4	3	3	3	3.7	Accept
5	Lack of awareness create issues with transparency	3	4	3	4	5	4	3	3	4	3	3.6	Accept
6	Lack of training hinder collaboration	4	2	4	3	4	5	4	3	4	3	3.6	Accept
7	Lack of training increase complication of protocols selection	2	4	2	4	5	4	5	4	3	2	3.5	Accept
8	Lack of training increase technological infeasibility	5	4	3	2	1	4	2	3	4	3	3.1	Accept
9	Lack of training increase issues with transparency	3	3	4	5	5	4	5	4	3	5	4.1	Accept
10	Issue with transparency hinder collaboration	4	2	3	4	5	3	4	5	4	4	3.8	Accept
11	Issue with transparency hinder willingness to adopt Blockchain	1	2	3	4	5	5	4	4	5	5	3.8	Accept
12	Issue with transparency hinder technical silos	3	5	4	5	4	5	4	5	5	4	4.4	Accept
13	Issue with transparency hinder regulatory	2	3	3	4	3	3	3	4	4	3	3.2	Accept
14	Issue with information sharing cause technical infeasibility	3	5	4	3	4	5	2	4	2	3	3.5	Accept
15	Technical infeasibility hinder protocol selection	4	4	3	4	5	4	3	2	3	4	3.6	Accept
16	Technology infeasibilities resistance to	3	4	4	5	4	3	2	3	5	5	3.8	Accept

	create technical silos												
17	Technological infeasibilities hinder willingness to adoption	5	4	3	5	4	4	4	3	4	5	4.1	Accept
18	Complicated protocols hinder technical silos	3	5	4	4	3	3	5	5	5	4	4.1	Accept
19	Complicated protocols hinder regulatory	2	4	1	5	4	3	2	4	3	3	3.1	Accept
20	Complicated protocols resistance to Blockchain adoption	5	4	3	4	5	4	5	5	4	3	4.2	Accept
21	Unclear regulatory hinder willingness to adoption	3	4	5	4	3	4	5	3	3	3	3.7	Accept
22	Unclear regulatory make system complex and costly	4	3	4	2	4	5	4	5	3	4	3.8	Accept
23	Costly setup hinder collaborations	1	2	2	2	3	1	2	3	3	2	2.1	Reject
24	Unclear regulatory resistance to technical	3	2	1	4	4	2	4	4	4	4	3.2	Accept
25	Resistance to technical silos make poor infrastructure	4	5	4	5	4	4	5	4	5	5	4.5	Accept
26	Poor system makes process complex	3	4	3	3	2	4	3	4	3	3	3.2	Accept
27	Costly setup hinder willingness	5	3	5	5	3	2	4	5	4	5	4.1	Accept
28	Unclear regulatory hinder collaborations	2	1	2	4	2	3	1	2	2	4	2.3	Reject
29	Poor infrastructure hinder willingness to adoption	2	3	5	4	5	4	5	4	5	4	4.1	Accept
30	Poor management involvement hinder collaboration	3	2	1	5	4	3	2	3	5	5	3.3	Accept
					Average score for the model							3.66	Accept

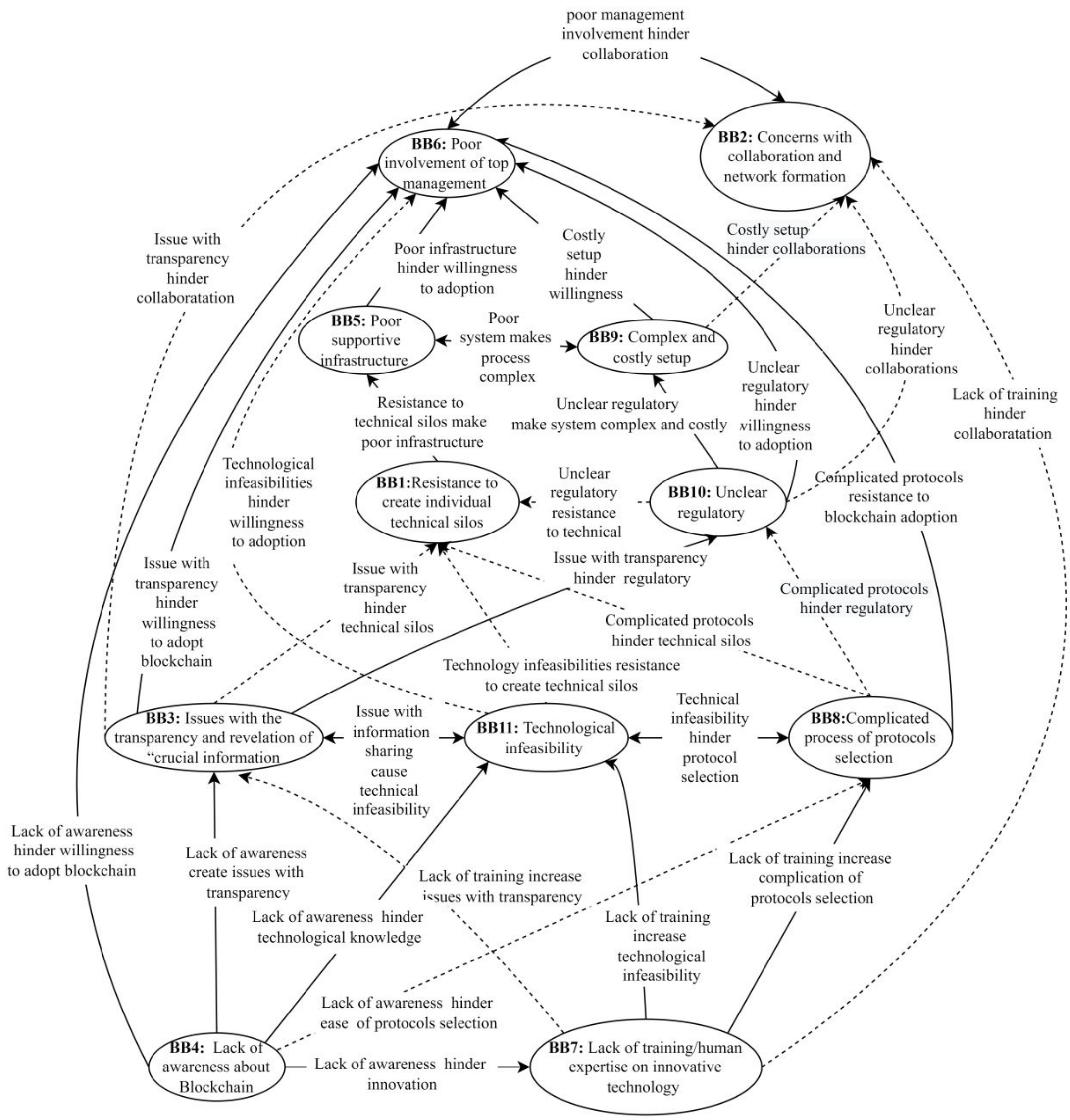

Figure 4: Validated mTISM model

4.2 MICMAC analysis

4.2.1 Step 1. Estimation of driving and dependence power

In this step, the driving and dependence power of each barrier is computed as shown in Table 11. Driving power is the sum of all the values in the row representing the factor in the final reachability matrix. Another side, dependence power is the sum of the values in the column representing the barrier.

4.2.2 Step 2. Construction of scatter plot

The barriers are classified into four groups based on their driving and dependence power as shown in scatter plot of Figure 5. Drivers are factors that have high driving power and low dependence power, whereas dependents show the opposite pattern (low driving power and high dependence power). Linkages are factors where driving and dependence power are both high, whereas, for autonomous factors, driving and dependence power are both low.

4.2.3 Step 3. Clustering of barriers

To identify the key barriers that hinder the adoption of Blockchain in GM, the defined barriers are classified into four clusters as driver, dependent, linkage, and autonomous. The clustering of barriers provides the predominant barriers that the manufacturing facility should tackle and control before the execution of the Blockchain technology.

Table 11: Driving and dependence power of Blockchain barriers

Barrier	BB1	BB2	BB3	BB4	BB5	BB6	BB7	BB8	BB9	BB10	BB11
Driving Power	3	2	6	6	3	2	6	5	5	5	6
Dependence Power	6	5	5	1	5	8	2	4	5	3	5

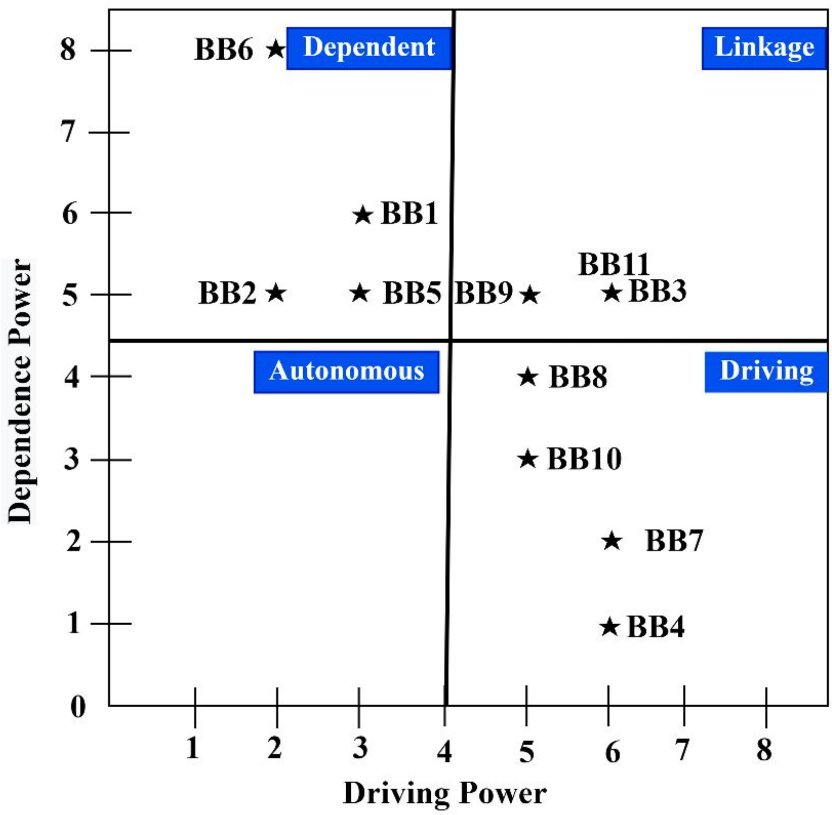

Figure 5: MICMAC analysis

5. Discussion of findings

In this study, eleven barriers of Blockchain adoption in manufacturing environment are modelled in five-level mTISM model as shown in Figure 4. The obtained model exhibits that barrier BB6 (Poor involvement of top management) and barrier BB2 (Concerns with collaboration and network formation) occupied the level 1, means these barriers are least influential barriers. It infers that these barriers may be influenced by other critical barriers, but not providing much impact on Blockchain adoption in manufacturing industries. The lack of awareness about Blockchain technology makes difficult for top management to decide about its adoption in their system. Due to complex setup of Blockchain, organizations may also depend upon Blockchain service providers. This may create insecurity in top management for sharing their transactional data with third party handler (Longo *et al.*, 2019). This may lead poor involvement of top management in Blockchain adoption, results hinder to make collaboration and network formations with external stakeholders. This outcome proposes that a poor administrative support in industries hampers implementation of Blockchain and similar line reported in literature also that poor support of top management act prime barrier in LSS implementation (Singh and Rathi, 2021). In a highly competitive market, even one weak link in the network can cause disruptions and delays, negatively impacting customer experience, which can significantly affect both the revenue and profitability of the company.

Level 2 in mTISM model is consisting two barriers BB5 (Poor supportive infrastructure) and BB9 (Complex and costly setup). The poor infrastructure of firms and costly setup of Blockchain leads to poor adoption of it in manufacturing setting. Barriers like BB1 (Resistance to create individual technical silos) and BB10 (Unclear regulatory) lies at third level of the TISM model. The standard government norms and regulations of Blockchain complicates the adoption process of it in manufacturing setting. Also, the challenge of implementing an urbane technology like Blockchain entails the high-level managerial and operational technical skills.

In the level 4 of TISM model, the barriers BB3 (Issues with transparency and revelation of 'crucial information'); BB11 (Technological infeasibility); and BB8 (Complicated process of protocol selection) are the interlinked with entire system due to make connection with other levels. When top management of firms are not ready to share true data among their employee and external venders, then it becomes tough to execute Blockchain to obtain actual benefits (Wang, Han, *et al.*, 2019). Finally, two barriers BB4 (Lack of awareness about Blockchain) and BB7 (Lack of training/human expertise on innovative technology) exists at the bottom level of model and found the most influential barriers. The adoption of Blockchain is hampered when firm owners are unfamiliar with the technology and have a cloudy understanding of how it can benefit them in the future (Goyat *et al.*, 2019). These are the most significant obstacles because Blockchain is still in its early stages and there are not any well-known case study exists to successful initiation. Literature also reveals that poor technical knowledge about Blockchain found the most critical barriers of Blockchain adoption in supply chain (Kaur *et al.*, 2024). But the present study exhibits the modelling of barriers of Blockchain in context of manufacturing industries that could take initiative to adopt Blockchain by controlling the barrier at initial stage.

In the addition, the significant barriers with their relationship are highlighted based on driving and dependence power in MICMAC analysis. The first quadrant includes the autonomous barriers, which do not have either positive or negative affect on system due to their low driving and dependence powers (Mathivathanan *et al.*, 2021). In this study, no autonomous barriers exist, but in case, if any autonomous factors are present, then they must be considered as driving factors.

The second quadrant includes the barriers BB4 (Lack of awareness about Blockchain), BB7 (Lack of training/human expertise on innovative technology), BB8 (Complicated process of protocol selection), and BB10 (Unclear regulatory), which consists high driving power but low dependence power. As a result, these are the most significant barriers that should be tackle on top priority and removed first while adopting Blockchain technology because they may serve as the root cause of other barriers.

The third quadrant consists such barriers which offers stability to the whole system and minor change in these can cause of disturbance in entire system (Meena *et al.*, 2021). The barriers of this quadrant are having high driving and dependence power. The barriers BB9 (Complex and costly setup); BB3 (Issues with transparency and revelation of 'crucial information'), and BB11 (Technological infeasibility) exist in the cluster of linkage factor. These barriers are having an essential role to drive the entire system due to possess high strength and also have the capability to disturb the system if not tackled simultaneously due to high dependence power (Dhir and Dhir, 2020).

The fourth quadrant occupies those barriers which are extremely dependent on the other barriers in the system, but have low driving power to interrupt the system individually (Patel *et al.*, 2021). The barrier BB6 (Poor involvement of top management), BB2 (Concerns with collaboration and network formation), BB5 (Poor supportive infrastructure), and BB1 (Resistance to create individual technical silos) fall in this category. It reveals that these barriers are not prime cause of poor Blockchain adoption, but affects indirectly to adoption of Blockchain in the system. Moreover, their degree of affect is dependent upon various other barriers. Overall, in line with literature (Mathivathanan *et al.*, 2021), our study reveal that with good knowledge and awareness of the Blockchain, establishing technological competence within the system, proper setup with experts participation facilitates to industries for successful Blockchain adoption.

Despite of industrial implications, this study provides significant contribution towards theoretical knowledge also. In context of theoretical contribution, this study exhibits an extensive, encompassing advancements in technology adoption theories, context-specific insights, interdisciplinary integration, strategic and managerial implications, policy and regulatory insights, enhancement of innovation diffusion models, socio-technical systems theory, and empirical validation and theory testing. By addressing these areas, the study not only advances academic knowledge about Blockchain in manufacturing, but also provides practical guidance for industry stakeholders.

6. Implications of study

6.1 Theoretical implication

The present research work offers significant theoretical contribution towards existing knowledge of Blockchain adoption in general and the barriers of Blockchain adoption in manufacturing industries in specific. First, this study is conducted first time to highlight the critical barriers of Blockchain adoption in manufacturing industries. Second, the identified barriers are modelled to explore the contextual relationship among them using mTISM-MICMAC approach. In literature, none of research studies examined the contextual relationship among barriers of Blockchain adoption in manufacturing industries using novel approaches like mTISM-MICMAC analysis. The MICMAC analysis also provides insight for researchers to explore the identified barriers into various clusters like dependent, autonomous, independent, and linkage barriers to examine their nature.

Finally, the identified barriers are set into different levels in the proposed mTISM model, which provides the hierarchy of barriers for researchers to recognize the interconnections among barriers. This study is not only providing a robust methodological contribution by considering novel approach of mTISM-MICMAC, but also offer a clear understanding of mutual relationship among barriers and across various levels. In future, the researchers can drive the empirical relationship between key barriers by using our proposed mTISM model.

6.2 Managerial implication

This study provides implications for industrial managers by proposing mTISM model of barriers which needs to control prior for adoption of Blockchain in their existing manufacturing setting. The obtained results reveal that lack of awareness about Blockchain and poor training/human expertise on innovative technology could make hinders Blockchain adoption in firms to the most. As a result, managers should remove these critical barriers by conducting training sessions with top management, as well as for employee to develop the environment for Blockchain adoption, how it works and what benefits it could bring to the firm. In this manner, managers may ensure to cop up the collaboration among external stakeholders and venders to make further easing the adoption process. The proposed MICMAC model highlights the key barriers with their driving and dependence power. The managers can pay attention on these barriers as per categories in MICMAC analysis and may assess them as per the current situation by analysing each barrier individually from their firm's perspective. Accordingly, managers can establish practises to eliminate them tactically on the path to successful Blockchain technology adoption in their firms. Also, managers, and industrialist can frame the policy, strategies, and guidelines for Blockchain adoption in the manufacturing environment by considering the obtained results of the present study.

7. Conclusion

This study identified and analysed the barriers to Blockchain adoption in manufacturing industries. The barriers were identified through the comprehensive literature review and further the contextual relationship among them has been developed by using mTISM approach. The mTISM examines the active interactions and transitive linkages between the barriers and developed a hierarchical model with interpretation of transitive links among barriers to Blockchain adoption in the manufacturing setting. This study also explored the dominant barriers those must be tackled and removed from the manufacturing system on priority basis to adopt Blockchain successfully. Further, MICMAC has been applied to recognize the vital barriers that delay the adoption of Blockchain in manufacturing setting. The combined mTISM and MICMAC approach provided the driving barriers that must be removed first so that the other dependent barriers in the system can also be eliminated. The obtained results exhibited that lack of awareness about Blockchain and poor training/human expertise in innovative technology are the most influential barriers, which trigger dependent barriers. This research work will facilitate to industrial managers to recognize the driving barriers that need to be removed for smooth adoption of Blockchain in manufacturing organisations. Also, the managers should emphasis on enhancing the knowledge about Blockchain functionalities with their employees and enlighten the top management with Blockchain adoption benefits for the firms. Overall, this research provides the impetus to manufacturing industries for mapping the potential of Blockchain with their own business for successful adoption of Blockchain technology.

7.1 Limitation and future research direction

In the present research work, the barriers to adoption of Blockchain in manufacturing setting were analyzed subjectively through mTISM approach, which not quantified mathematically. The mTISM approach lacks to weight estimation of barriers to explore their relative significance, thus Structural Equation Modelling (SEM) can be used in future to validate the proposed model. The Fuzzy set theory and grey analysis can be used for fuzziness of experts and to diminish the drawback of limited number of responses. Moreover, the mutual dominance of barriers with causal-effect diagram can be quantified through adoption of Decision-Making Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP) etc. in future. In addition, the proposed model can be tested along with questionnaire using confirmatory factor analysis in the future, which was not overlooked in this study.

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