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Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry

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ABSTRACT

The aim of this paper is the analysis of potential barriers which would hinder the manufacturing organizations from embracing Industry 4.0. This paper establishes relationships among the barriers using interpretive structural modeling (ISM) and finds out driving and dependence power of barriers, using fuzzy MICMAC (Matriced' Impacts Croise´s Multiplication Applique´e a´ un Classement) analysis. A group of experts from industry and academia was consulted and ISM methodology was used to develop the contextual relationship among the identified barriers to Industry 4.0 adoption. The results of ISM were used as input to fuzzy MICMAC analysis for determining the driving and dependence power of the Industry 4.0 adoption barriers. The results are helpful in identifying and classifying the significant barriers, revealing the direct and indirect effects of each identified barrier on the Industry 4.0 adoption. The findings will help the practitioners and the policymakers for a detailed understanding of the Industry 4.0 adoption process and the barriers hindering its implementation. They may utilize the framework and the driving-dependence power of the barriers to understanding the inter-relationship between the barriers to building a valid and operative digital manufacturing platform. The study is first of its kind to identify industry 4.0 adoption barriers and develop hierarchical relationships between them using ISM and fuzzy MICMAC methodology in the Indian manufacturing context.

1. Introduction

Industry 4.0, a German strategic initiative, is aimed at creating smart factories where various emerging technologies like big data analytics, internet of things, additive manufacturing, virtual reality, cloud computing, robotic systems are deployed to achieve cyber-physical systems (CPS) and human-equipment interface leading to economic, environmental and socially sustainable manufacturing systems [1–4]. Often referred to as the fourth industrial revolution, industry 4.0 first appeared in an article published in November 2011 by the German government that resulted from an initiative regarding high-tech strategy for 2020 [5]. The invention of the steam engine catapulted the first industrial revolution, second industrial revolution focused on mass production, third industrial revolution emphasized computing [6,7], and the fourth industrial revolution is the digital revolution in industrial production which is emerging from enhanced networking and computerisation of all areas of production [8]. The crux of industry 4.0 is the emergence of digital manufacturing aka "*smart factory*," which means smart networking between industry units, mobility in processes, the flexibility of industrial operations and their interoperability, integration with customers and suppliers and in the adoption of innovative business models [9]. The crucial aspect associated with industry 4.0 is the intelligent networks based on CPS [10]. Industry 4.0 integrates the digital and physical world using the CPS providing increased productivity and efficiency among the organizations [11]. The CPS comprises smart machines, storage systems, and production facilities which can exchange information, triggering actions and controlling each other independently [12]. Industry 4.0 integrates the use of big data, internet of things (IoT) and Artificial Intelligence (AI) as one [13] and has tremendous potential for the organizations to achieve economic and social benefits [14]. IoT has affected the way in which CPS can interact, monitored, controlled and managed thereby facilitating the integration of processes and systems across manufacturing sectors and technologies [15]. This contributes to better communication and cooperation with each production unit in a new intelligent way which revolutionizes production, improves services provision, enhances logistics and resource planning in an efficient and cost-efficient manner [16,17].

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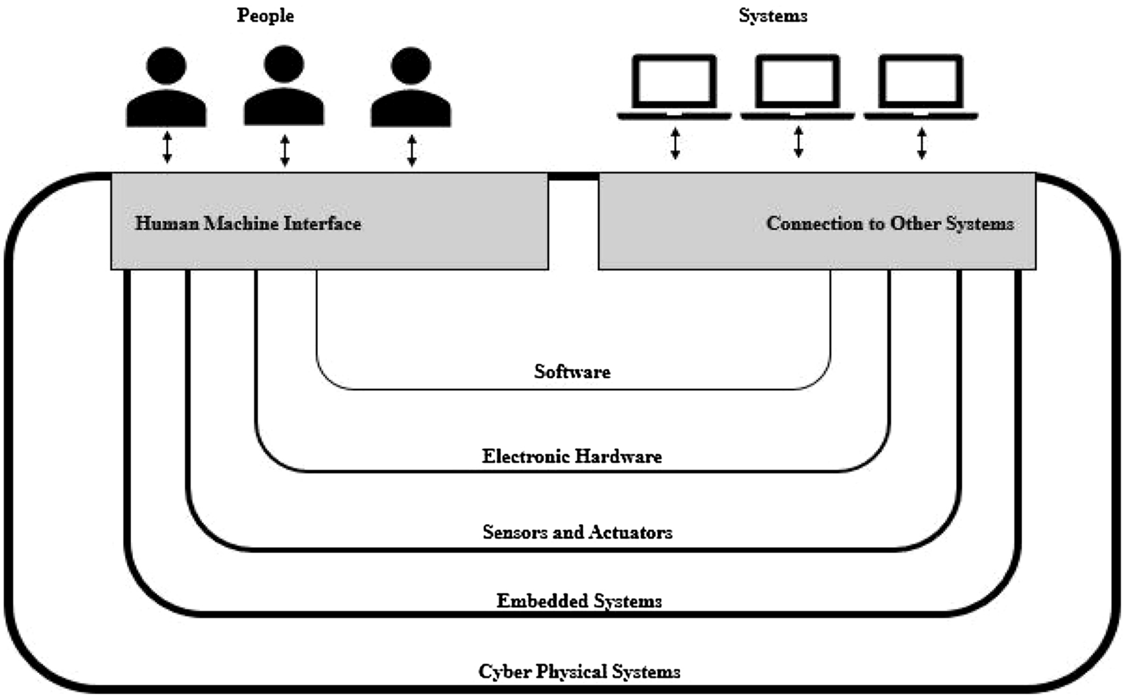

Fig. 1. Human and machine interaction in a CPS.

The manufacturing industry in India is fast becoming one of the most promising and prosperous sectors to look forward [18]. The manufacturing industry contributes 15–16% to national GDP and employs around 12 percent of the working population [19]. By the year 2022, the Indian manufacturing sector is estimated to increase its gross domestic product (GDP) to 25 percent and create 100 million new jobs [19]. The "Make in India" initiative launched by the Government of India with an objective of promoting the manufacturing ecosystem in India is bringing a positive outlook to this sector. As per the reports published by the Government of India, the manufacturing sector in India has witnessed an increase in the Gross Value Added (GVA) at a CAGR of 4.34 percent during the financial year 2012 and 2018. Deployment of the Internet of things and Industry 4.0 is slowly taking place through projects like the smart city and digital India [20]. The emerging technologies are believed to offer improved cost, productivity, quality, flexibility and employee satisfaction. However, the level of implementation level of these technologies and their applicability across industries in India is different. The manufacturing organizations are required to drive their specific agenda on the implementation of Industry 4.0. The benefits offered by Industry 4.0 presents a strong case for the Government, industry associations, and other policymakers to strongly put measures in place accelerating the adoption of Industry 4.0. Industry 4.0 can act as a strong driver of job creation and can be a key driver for enhanced productivity and competitiveness for Indian manufacturing [21,22] supporting the goals set by "Make in India" initiative. Srivastava [23] identifies defense, aviation, railways, automobiles & automobile components, electronics, pharmaceuticals, and textiles as the sunrise sectors in India with a potential to contribute $80-100 billion to India's GDP every year till 2025 given that this sector immediately adopts industry 4.0.

Industry 4.0 promises to advance the Indian manufacturing into the digital decade. It is therefore required to develop an ecosystem that is strong on Infrastructure, skill development, and policy. Industry 4.0 has the potential to change the appearance of Indian manufacturing [22]. Despite many advantages which industry 4.0 promises, there is still an air of uncertainty in the adoption of industry 4.0. A significant chunk of it lies in the high investment levels and the unclear cost- benefits for the industry 4.0 application areas [17]. Therefore, it is essential for the manufacturing sector in India to identify the barriers of Industry 4.0 adoption and understand the inter-relationships between them so that it helps the industry practitioners to overcome these barriers.

This paper attempts to identify the significant barriers to adoption of industry 4.0 in Indian manufacturing sector and suggest how the industry practitioners and policy makers must take steps in overcoming these barriers to successful adoption of Industry 4.0. A combined interpretive structural modeling (ISM) and fuzzy MICMAC analysis were used as the research methodology. This paper is organized as follows: In Section 2, we present a brief review of the literature and discuss the barriers to adoption of Industry 4.0. In Section 3 and 4, we discuss the ISM and fuzzy MICMAC methodologies in identifying the relationship between the barriers to adoption of industry 4.0. Section 5 presents the results and discussions. The conclusions, contributions, and recommendations for future research are presented in Section 6.

2. Review of literature

2.1. Industry 4.0 and its component

Kagermann et al. [24] initially published the key concepts of Industry 4.0 and have since then, laid the groundwork for the Industry 4.0 strategy. Identifying the potential of Germany as a global leader in manufacturing, the author trusts Germany to capitalize on its technical prowess and tap into the possibility of industry 4.0. They further advocate the concept of Industry 4.0 facilitating the connection of information, objects and people due to the creation of physical and virtual manufacturing worlds enabling the transformation of factories into smart manufacturing environments. The focus of industry 4.0 is in establishing intelligent products and production processes [25]. The critical components of industry 4.0 are CPS, IoT, Internet of Services (IoS) and Smart Factories [26]. Shafiq et al. [27], define CPS as "the conjunction of the physical and digital worlds by creating global networks for businesses that integrate their technology, warehousing systems, and production facilities." The various operations of the physical systems are integrated using physical functionalities through networking using computing and communication infrastructures [28–30].

2.2. Human-Equipment interaction in CPS

Fig. 1 shows the components of human-equipment interaction in a CPS environment. The CPS comprises different technology components that include the embedded systems, sensors, hardware and software. Embedded systems act as one of the significant technical methods that facilitate integrated interaction between the physical objects and their computational elements or services associated with them. In a production system, sensors play an important role in the operation of the IoT and CPSs. A sensor is defined as "a mechanical device sensitive to light, temperature, radiation level, or the like, that transmits a signal to a measuring or control instrument." It is a useful device that collects and transmits the manufacturing process information in real-time to the computers [31].

The collection and exchange of data are possible through the CPS, which interconnects and networks various objects that are embedded electronic sensors, actuators, or other digital devices [32,33]. Different software are required for computing the real-time data, maintaining data security and privacy, and controlling the hardware equipment's deployed in the CPS [34]. The hardware components include 3D printers, robotic systems and other equipment's. The CPS operates in an IoT ecosystem that combines intelligent and autonomous machines, advanced predictive analytics, and machine-human collaboration to improve productivity, efficiency, and reliability [35,36].

2.3. Smart factory

Like IoT, IoS is emerging, based on the idea that services are made readily available through web technologies, allowing companies and private users to combine, create and offer new kind of value-added services [37]. A Smart Factory is built on the concept of a decentralized production system, in which humans, machines, and resources communicate with each other, like a social network enabled by IoT, IoS and CPS [14].

Fig. 2 shows the visualization of a smart factory. By equipping manufacturing with sensors, actuators, and autonomous systems, Industry 4.0 will help in making factories more intelligent, flexible, and dynamic. Equipment and machines will thus be able to achieve higher levels of self-optimization and automation. In addition to this, the manufacturing process will then have the capacity of fulfilling more complex and help in meeting competent standards and requirements for products [38]. Smart manufacturing and intelligent factories are the significant areas of focus for industry 4.0 [39,40].

2.4. Barriers to adoption of industry 4.0 (BTA)

For research and application, industry 4.0 is a crucial area as it offers value addition to the manufacturing outputs and systems by integrating emerging technologies in manufacturing and services [41]. However, organizations still have a mountain to cross for the successful and timely implementation of the digital concepts. The main reasons for the uncertainties lie in the high investment levels and the unclear cost-benefits for the industry 4.0 application areas. Further, the workforce lacks the adequate skills required to cope up with the upcoming automation and there is a lack of clarity in the standards for the implementation of industry 4.0 which has created ambiguity in many organizations. This digital change will need to cross many hurdles before being successfully embraced wholeheartedly by all organizations [17,31,42].

In this study, the BTAs for Industry 4.0 is identified based on extant literature review and opinions of experts from industry and academia. A two-phase process was used for the selection of the BTAs. In the first phase, fifteen BTAs were identified based on the literature review. The review considered research articles on Industry 4.0 published in Web of Science, Scopus and Emerald Insights. Few industry reports, news articles, and trade magazines were also referred for more information on Industry 4.0 and the barriers affecting its implementation. The search keyword used included terms like Industry 4.0, digital manufacturing, smart manufacturing, Industry 4.0 opportunities and challenges, Industry 4.0 benefits, limitations, and Industry 4.0 implementation. In the second phase, these fifteen barriers were validated and improved further by a team of fourteen experts drawn from different background resulting in the final selection of twelve BTAs for Industry 4.0 suitable to the Indian manufacturing context. The group of experts comprised of three academicians from Industrial Engineering and Manufacturing Systems area, two academicians from Operations and Supply Chain Management area, three senior IT engineers, two senior managers from the automotive sector working in manufacturing domain, two senior

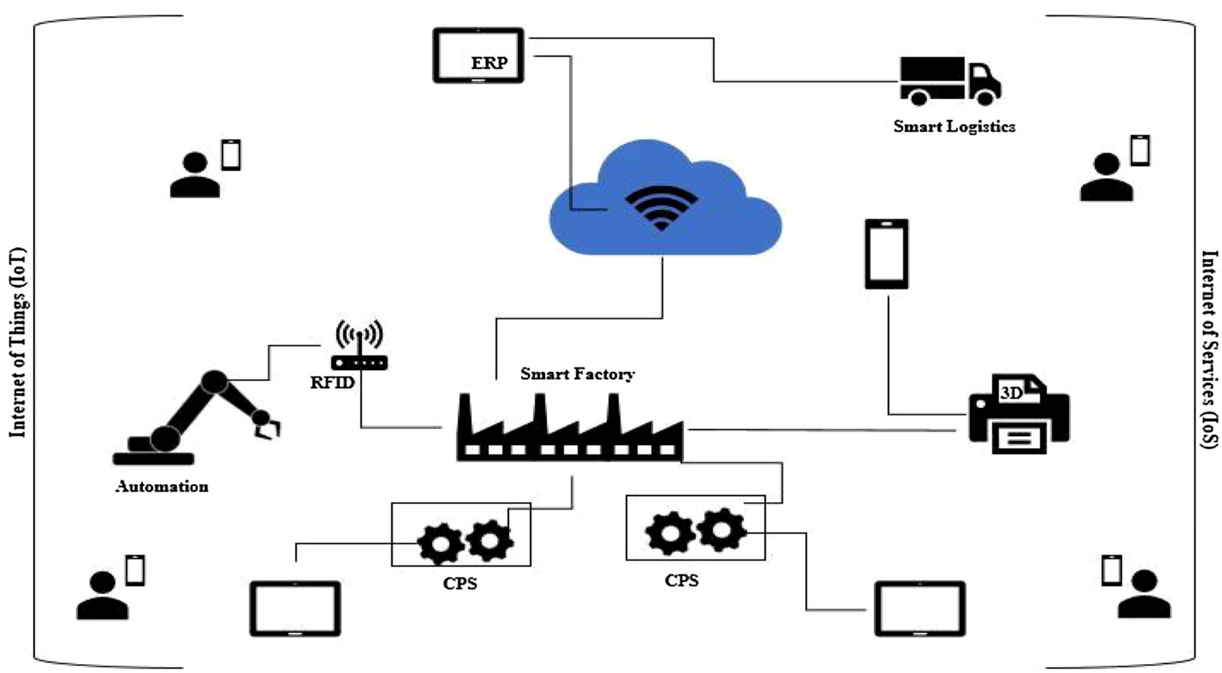

Fig. 2. Visualisation of a smart factory.

Table 1
BTAs for industry 4.0.

Sl. No.	Industry 4.0 adoption barrier	Description
1	Employment Disruptions (BTA1)	It is defined as the disruptions brought in the employment due to the emerging technologies and automation. Current jobs in the manufacturing sector are prone to be automated resulting in human job losses [46]. The residual manufacturing jobs will comprise more knowledge work as well as more short-term and hard-to-plan tasks [47].
2	High Implementation Cost (BTA2)	This refers to the capital expenditure which the organizations will have to incur for developing the industry 4.0 infrastructure in their organizations. Industry 4.0 is difficult to adopt in small and medium industries as there is a lack of fund for appropriate technologies [48]. Emerging technologies such as IoT, always carry a noteworthy threat for investments to organizations as there can be potential financial losses and no recovery of investments [49,1].
3	Organizational and Process Changes (BTA3)	This refers to the process changes which will be prompted due to the advent of CPS and smart factories. Organization functions may change owing to automation Industry 4.0 will give rise to decentralized organizations. Decision making will lie at the shop floor level [50]. By far and large, IoT applications and solutions, despite being beneficial across industries carry significant challenges which pertain to the internal and external integration of vertical, heterogeneous, and closed systems. These are recognized as significant concerns for most of the enterprises [51–55].
4	Need for Enhanced Skills (BTA4)	With the implementation of the Industry 4.0, the skills and qualifications of the workforce will become the key to success of a highly innovative factory [56]. The companies should be focused on the development of qualified workforce by the Human Resources Management [57]. Efficient design and deployment of IoT solutions require a lot of prerequisite knowledge which cuts across various technical and non- technical disciplines [58,59].
5	Lack of knowledge management systems (BTA5)	Knowledge management systems refer to information technology systems that store and retrieve knowledge, improve collaboration, locate knowledge sources, mine repositories for hidden knowledge, capture and use knowledge, and enhance the knowledge management process. Knowledge management can benefit by embedding IoT and processing incoming big data collected from IoT devices [60] however; the existing systems may not handle the real-time data. Comprehensive technical skills are needed to switch from operational to more strategic tasks [61,62]. Shortly, there will be demand for data analysts who will create value through optimization and forecasting [63].
6	Lack of clear comprehension about IoT benefits(BTA6)	IoT is defined as the network of physical devices embedded with sensors, electronics, software, sensors, actuators, and connectivity for sending and receiving data. No doubt the adoption of IoT in new businesses is related to potential financial gains. On the contrary, enterprises must have a clear-cut understanding regarding the nuances of IoT deployment, i.e., of value creation, delivery, and capture. Enterprises should evaluate the variances accordingly if they are to consider the business model with IoT applications [64–66]. Several applications and technologies from IoT are still in the initial development stages [58]. There lies an uncertainty in the potential cost-benefit expectations that may be derived from the deployment of IoT. Hence, IoT deployment is deemed as a crucial encounter faced by most of the industries. [1,58,67].
7	Lack of Standards and Reference Architecture (BTA7)	The design and selection of an Industry 4.0 architecture for different applications have been a significant challenge particularly if we consider wireless sensory network. As the concept of industry 4.0 is new, there is a lack of standards and reference architecture [31,42]. For example, the formation of efficient IoT architecture throughout supply chains involving objects, network, data services, and applications layers is perceived as a significant barrier to successful IoT adoption [68–72].
8	Lack of Internet coverage and IT facilities (BTA8)	Refers to the lack of IT infrastructure that is required to support the Industry 4.0 implementation. IoT plays a vital role in Industry 4.0 framework. Lack solutions for effective communication and signal coverage may act as a significant blockade for various products/ services. Signal attenuation occurs due to weak signal coverage in certain manufacturing premises [73–75].
9	Security and Privacy Issues (BTA9)	There is a huge amount of information flow that occurs on the Industry 4.0 platform posing cybersecurity threat and data privacy issues. Virtual work on servers or platforms obligates employees to be aware of cyber security [76]. A critical aspect of the CPS is cybersecurity. CPS is more susceptible to cyber-attacks with the recent advancements in IT [77,78]. Cyber-security risks related to verification, authorization, privacy, access to the system, applications, network, and data remain significant challenges for the organizations [79].
10	Seamless integration and compatibility issues (BTA10)	These are the issues which may arise while upgrading the existing machines and equipment for the industry 4.0. Establishing seamless integration and interoperability between different technologies and network systems is one of the significant barrier associated with the adoption of IoT solutions to create a cyber-physical infrastructure of IoT ecosystems [53,54,55,67,80].
11	Regulatory Compliance issues (BTA11)	Regulatory compliance refers to the goal that organizations seek to achieve in their efforts to ensure that they are aware of and take essential steps to comply with applicable laws, policies, and regulations [81]. Organizations need to have stricter rules in place for IT security, working with the machine, or working hours [82,83].
12	Legal and Contractual Uncertainty (BTA12)	Digitalization poses a challenge for the law as the competition gets fierce. Laws about data protection, liability for artificial intelligence, standardization must be considered while deploying a digital strategy [84]. Without a legal personality, the virtual organization does not legally exist and so cannot be identified as a legally independent entity. Every virtual organization that uses ICT needs to guarantee that by transferring data online they do so in a secure manner, and they do not infringe privacy regulations or that the contracts concluded are valid and enforceable [85,86].

automation engineers, and two senior engineers from the telecommunication sector. Previous research studies have highlighted that the suitable number of experts for carrying out qualitative research may range from five to 50 [43]. Murry and Hammons [44,45] reported that the ideal number of experts might be in the range of 10 to 30 for the qualitative decision-making process. Hence the selection of fourteen experts was justified. The list of BTAs for Industry 4.0 with a brief description is presented in Table 1.

3. ISM methodology and model development

Warfield [87] proposed ISM with the purpose of analyzing the complex socio-economic systems in the form of a map showing complicated relationships between many elements involved in the selected complex systems. The complex system is decomposed into several subsystems (elements) to develop a multilevel structural model based on the knowledge extracted from the experts based on their experience and expertise. ISM methodology has been used to analyze the complexity of relationships by many researchers. (See Table 2).

ISM methodology was used for the following characteristics as observed by Raj et al. [92]:

i *Interpretive*- The relationships between the elements are based on judgments of a group of experts from the selected field.
ii *Structural*- the overall structure on the basis of the relationships is extracted from the complex set of variables.
iii *Modeling technique*- the outcome is a diagraph model based on the relationships and extracted structure.

Table 2
ISM Applications.

Sl. No.	Author	ISM application	Main Findings
1	Cherrafi et al. [88]	Green Lean implementation barriers	'Lack of environmental awareness' and 'lack of government support to integrate green practices' were identified as the active driving barriers.
2	Rane and Kirkire [89]	Risk sources in medical device development (MDD) process.	'Poor communication among device developers, end users, and marketing people,' 'ambiguity about end users and their requirements,' 'poor translation of user requirements to device design parameters' and 'improper or poor assessment of progress by reviewers' were identified to have strong driving power.
3	Darbari et al. [112]	Dominant barriers, which create hindrance in the adoption of the sustainability in the Indian food industry	The study identifies 'lack of governmental leadership in outlining the vision for Sustainability responsibilities of food retailers" and 'lack of financial resources 'as the significant barriers to adopting sustainability in Indian food supply chains.
4	Kumar et al. [115]	The relationships between the Barriers in green lean six sigma product development process.	The study identifies 'Lack of Real Support of Management,' 'Fund Constraints', 'Lack of Expertise Training Program', 'Poor Quality of Human Resources', 'Unsupportive Culture & Lack of Motivation and Encouragement', 'Lack of KAIZEN Environment', 'Supplier unwillingness to Transform towards Green lean six sigma and Poor Raw Material Quality' as the critical drivers in implementation of green lean six sigma product development process.
5	Thakur and Anbanandam [90]	Studied barriers that hinder India's healthcare waste management (HCWM) systems	The study identified 'Motivation',' Knowledge and training', 'Infrastructure', 'Commitment among hospital administrators', 'Budget', 'Appreciation', 'Segregation', 'Self harm', 'Clinical commitment', 'Convenience', and 'BMW handling rules 'as the significant driving barriers for HCWM systems.
6	Diabat et al. [91]	The barriers to third-party logistics (TPL) implementation	The study identified 'Lack of qualification for employees in TPL provider' and 'fear of employees of the firm' as the driving variables.

However, Kannan et al. [93], point that the results of the ISM may not be free from the bias of the person who is evaluating the elements.

The steps used in incorporating ISM methodology are as follows;

1 Identification of Industry 4.0 adoption barriers- as discussed in Section 2.3 the BTAs for Industry 4.0 adoption are derived theoretically based on literature review and validated by the experts from academia and industry. The list of BTAs is presented in Table 1.
2 Contextual relationship- From the identification of BTAs, a contextual relationship is identified among the barriers concerning whom the pairs of variables would be examined. After determining the barrier set and the contextual relation, a structural self-interaction matrix (SSIM) is prepared based on a pair-wise evaluation of BTAs of Industry 4.0.
3 Developing the reachability matrix- From the SSIM, reachability matrix is established and checked for transitivity. The property of transitivity allows an additional path for the reachability matrix, which is filled by inference, i.e., if A→C (A is related to C) and C→D (C is related to D), it may be inferred that A→D (A is related to D) [94].
4 Developing the level partitions: The level partitions are obtained from the reachability matrix using the reachability and antecedent sets of each factor. The levels are obtained by carrying out the iterations.
5 Constructing the digraph- After the partitioning of the factors, a directed graph is drawn by joining the vertices or nodes. The ISM which is the extraction of the structural model is developed by removing the lines of edges and the transitive links based on the relationships obtained in the reachability matrix. An extraction of the structural model, called ISM, is derived [95]

3.1. Developing the structural self- interaction matrix (SSIM)

For analyzing the barriers to adoption of Industry 4.0 the following symbols are used to indicate the direction of the relationship between the selected barriers (i and j) to develop the SSIM.

V = Criteria i will help achieve criteria j;
A = Criteria j will be achieved by criteria i;
X = Criteria i and j will help accomplish each other; and
O = Criteria i and j are unrelated.

The relationships were given by the fourteen experts, who were approached earlier for validating the identified barriers. The two authors based in India played the role of moderators in compiling the obtained responses to a usable form for this research work. In most of the cases, all the experts had consensus on the type of relationship existing between the two barriers based on discussions. However, in two cases, it was difficult to have agreement on the relationship. To resolve the issue, individual responses from the fourteen experts were collected and the final decision was based on the highest frequency assigned to V, A, X and O. Out of the two relationships that was considered through this process the first relationship had a frequency of eight for V (BTA3 and BTA10) and the second relationship had a frequency of eleven for O (BTA7 and BTA8).

These responses in the form of SSIM is shown in Table 3.

3.2. Initial reachability matrix

A binary matrix, called initial reachability matrix is developed by converting the values in SSIM table obtained in the previous step as presented in Table 4. The values V, A, X and O from Table 3 are substituted by 1 and 0 as per the following rules:

1 If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1, and the (j, i) entry becomes 0.
2 If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0, and the (j, i) entry becomes 1.
3 If the (i, j) entry in the SSIM is X, then the (i, j) entry in the reachability matrix becomes 1, and the (j, i) entry also becomes 1.
4 If the (i, j) entry in the SSIM is O, then the (i, j) entry in the reachability matrix becomes 0, and the (j, i) entry also becomes 0.

The final reachability matrix after incorporating the transitivity as per the rules mentioned above is shown in Table 5. The transitivity analysis was performed using MATLAB program.

3.3. Level partitions

From the final reachability matrix, the reachability and antecedent set for each BTA are deduced. The reachability set consists of the BTA itself and the other BTAs, which it may help achieve, whereas the antecedent set comprises of the BTA itself and the other BTAs, which may assist in attaining it. For all the BTAs, the intersection of these sets is derived. The top level in the ISM hierarchy is occupied by the BTAs for whom the reachability and the intersection sets are same. The top-

Table 3
SSIM.

Industry 4.0 adoption barriers	BTA12	BTA11	BTA10	BTA9	BTA8	BTA7	BTA6	BTA5	BTA4	BTA3	BTA2	BTA1
BTA1	A	A	O	O	O	O	O	V	A	A	O	
BTA2	O	O	A	A	A	O	V	O	A	A		
BTA3	O	A	V	A	V	A	O	A	V			
BTA4	A	A	A	A	A	A	O	V				
BTA5	O	A	V	V	O	O	O					
BTA6	A	A	A	A	A	A						
BTA7	A	V	V	A	O							
BTA8	O	O	V	V								
BTA9	A	V	V									
BTA10	A	A										
BTA11	A											
BTA12												

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9); Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

level BTA in the hierarchy would not help achieve any other BTA above its level. Once the top-level BTA is identified, it is separated out from the other BTAs. At the next level, the same process is repeated to find out the other BTAs. This process is continued until the levels of each BTA are found out. The identified levels (see Table 6) help in building the digraph and the final model of the ISM.

3.4. Formation of ISM based model

From the final reachability matrix (Table 5), the structural model is generated. If there is a relationship between the BTAs i and j, this is shown by an arrow which points from i to j. This graph is called a directed graph, or digraph and is shown in Fig. 3.

4. ISM fuzzy MICMAC analysis

When the ISM model is developed, the relationship amongst two variables is denoted by “0” and “1”. The occurrence of a relationship is denoted by 1 and 0 in case of no relationship. However, the relationship between two BTAs cannot be equal in all scenarios; some might have a stable relationship, some might have a strong relationship, some might have a very reasonable relationship, some might have a weak relationship, and some might have a fragile relationship. The binary input will be ‘1’ for all the above cases in ISM. To overcome this shortcoming of the ISM based model, a fuzzy form of ISM is used for MICMAC analysis. Many researchers have used ISM Fuzzy MICMAC analysis in their studies; this is shown in Table 7 below.

4.1. Binary direct reachability matrix (BDRM)

To obtain the BDRM, the interactions between the BTAs are referred from Table 3, i.e., the initial reachability matrix. To achieve the BDRM, all the diagonal entries in Table 3 are replaced by zero. The BDRM derived is represented in Table 8.

4.2. Construction of fuzzy direct reachability matrix (FDRM)

To further improve the analysis, we consider the strength of relationships instead of just considering the relationships. The strength of relationship means the strength of BTA *i’s* impact (given its occurrence) on BTA *j’s* probability of occurrence [99]. The strength of BTAs impact can be defined by a qualitative consideration on a 0–1 scale, as shown in Table 9.

The same fourteen experts who had validated the BTAs for Industry 4.0 and had given their inputs for the ISM-SSIM development were approached again to rate the relationship between the variables. The following assignment rule was used for establishing the fuzzy-based relationship between the BTAs (Table 10).

Table 4
Initial Reachability Matrix.

Industry 4.0 adoption barriers	BTA1	BTA2	BTA3	BTA4	BTA5	BTA6	BTA7	BTA8	BTA9	BTA10	BTA11	BTA12
BTA1	0	0	0	0	1	0	0	0	0	0	0	0
BTA2	0	0	0	0	0	1	0	0	0	0	0	0
BTA3	1	1	0	1	0	0	0	1	0	1	0	0
BTA4	1	1	0	0	1	0	0	0	0	0	0	0
BTA5	0	0	1	0	0	0	0	0	1	1	0	0
BTA6	0	0	0	0	0	0	0	0	0	0	0	0
BTA7	0	0	1	1	0	1	0	0	0	1	1	0
BTA8	0	1	0	1	0	1	0	0	1	1	0	0
BTA9	0	1	1	1	0	1	1	0	0	1	1	0
BTA10	0	1	0	1	0	1	0	0	0	0	0	0
BTA11	1	0	1	1	1	1	0	0	0	1	0	0
BTA12	1	0	0	1	0	1	1	0	1	1	1	0

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9); Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

Table 5
Final Reachability Matrix.

Barriers	BTA1	BTA2	BTA3	BTA4	BTA5	BTA6	BTA7	BTA8	BTA9	BTA10	BTA11	BTA12
BTA1	1	1	1	1	1	1	1	1	1	1	1	0
BTA2	0	1	0	0	0	1	0	0	0	0	0	0
BTA3	1	1	1	1	1	1	1	1	1	1	1	0
BTA4	1	1	1	1	1	1	1	1	1	1	1	0
BTA5	1	1	1	1	1	1	1	1	1	1	1	0
BTA6	0	0	0	0	0	1	0	0	0	0	0	0
BTA7	1	1	1	1	1	1	1	1	1	1	1	0
BTA8	1	1	1	1	1	1	1	1	1	1	1	0
BTA9	1	1	1	1	1	1	1	1	1	1	1	0
BTA10	1	1	1	1	1	1	1	1	1	1	1	0
BTA11	1	1	1	1	1	1	1	1	1	1	1	0
BTA12	1	1	1	1	1	1	1	1	1	1	1	1

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9); Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

Table 6
Level partitions and iterations.

Industry 4.0 adoption barriers	Reachability Set	Antecedent Set	Intersection Set	Level
Iteration I				
BTA1	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA2	2 6	1 2 3 4 5 7 8 9 10 11 12	2	
BTA3	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA4	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA5	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA6	6	1 2 3 4 5 6 7 8 9 10 11 12	6	I
BTA7	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA8	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA9	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA10	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA11	1 2 3 4 5 6 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA12	1 2 3 4 5 6 7 8 9 10 11 12	12	12	
Iteration II				
BTA1	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA2	2	1 2 3 4 5 7 8 9 10 11 12	2	II
BTA3	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA4	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA5	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA6		1 2 3 4 5 7 8 9 10 11 12		I
BTA7	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA8	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA9	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA10	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA11	1 2 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	
BTA12	1 2 3 4 5 7 8 9 10 11 12	12	12	
Iteration III				
BTA1	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA2		1 3 4 5 7 8 9 10 11 12		II
BTA3	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA4	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA5	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA6		1 2 3 4 5 7 8 9 10 11 12		I
BTA7	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA8	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA9	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA10	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA11	1 3 4 5 7 8 9 10 11	1 3 4 5 7 8 9 10 11 12	1 3 4 5 7 8 9 10 11	III
BTA12	1 3 4 5 7 8 9 10 11 12	12	12	
Iteration IV				
BTA12	12	12	12	IV

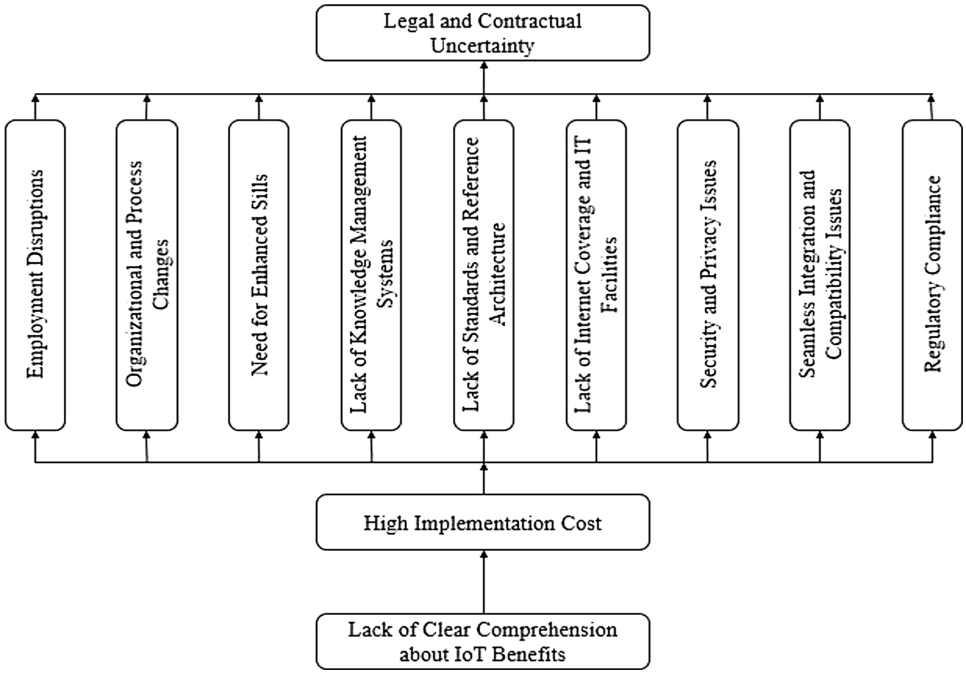

Fig. 3. ISM model.

Table 7
ISM Fuzzy MICMAC analysis as reported in the literature.

Sl. No.	Author	Details of Study
1	Khurana et al. [96]	Variables studied: Information Sharing Enablers for building Trust in Indian Manufacturing Industry The technique used: Integrated ISM and Fuzzy MICMAC
2	Dubey and Ali [113]	Variables studied: Flexible Manufacturing System Dimensions The technique used: Total ISM and Fuzzy MICMAC Analysis
3	Sindhu et al. [97]	Identified and analyzed the barriers to implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach
4	Dubey and Singh [114]	Variables studied: JIT, lean behavior, TQM and their antecedents Technique used: ISM and fuzzy MICMAC analysis
5	Dewangan et al. [98]	Variables Studied: Enablers for Competitiveness of Indian Manufacturing Sector The technique used: ISM-Fuzzy MICMAC Analysis
6	Sarkar and Panchal [116]	Variables Studied: Project risk management of ports The technique used: ISM and Fuzzy MICMAC
7	Sindhwani and Malhotra [117]	Variables Studied: Agile manufacturing system enablers The technique used: ISM and MICMAC analysis

Table 8
Binary Direct Relationship Matrix.

Industry 4.0 adoption barriers	BTA1	BTA2	BTA3	BTA4	BTA5	BTA6	BTA7	BTA8	BTA9	BTA10	BTA11	BTA12
BTA1	0	0	1	0	0	1	0	0	1	0	0	0
BTA2	1	0	1	0	1	1	0	0	0	1	0	0
BTA3	0	1	0	1	1	0	0	0	1	1	0	0
BTA4	1	1	0	0	0	0	0	1	0	1	0	1
BTA5	0	1	1	1	0	0	0	1	1	0	1	1
BTA6	1	1	1	0	0	0	0	0	0	0	1	0
BTA7	1	1	0	0	0	0	0	1	1	1	1	1
BTA8	1	1	1	0	1	0	1	0	0	1	0	0
BTA9	1	1	1	1	0	0	1	1	0	0	1	0
BTA10	0	0	1	1	0	0	1	0	1	0	0	0
BTA11	1	0	1	0	1	1	1	0	1	0	0	1
BTA12	1	0	1	1	1	1	1	0	0	0	1	0

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9); Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

Table 9
Fuzzy scales for defining the strength of BTAs.

Strength	NO	WEAK	MEDIUM	STRONG	VERY STRONG
Numerical Value	0	0.25	0.5	0.75	1

Number of experts agreed that the factor i drive factor j	Value Assigned
None	0
1–5	0.25
5–9	0.5
9–13	0.75
13 and above	1

These values are then superimposed on the initial reachability matrix; the resulting FDRM is represented by Table 11.

4.3. Fuzzy MICMAC stabilized matrix

There are three types of fuzzy compositions to determine the strength of the fuzzy indirect relation from element i to j: max-min, max-product and max-average [100]. In the context of this research, the max-min composition is the most suitable, since the fuzzy relations represent the strength of relations. This means that the minimum strength must be the maximum of all possible minimal impacts from i to j.

For achieving the stabilized fuzzy matrix, the matrixes are multiplied consequently till the stabilization is achieved for hierarchies of driving and dependence power. For multiplying the two matrixes, the basic principle of fuzzy multiplication is used [101,102]. The fundamental of fuzzy matrix multiplication is a simplification of Boolean matrix multiplication. As per fuzzy set theory, the outcome is always a fuzzy matrix when two fuzzy matrixes are multiplied. The rule to multiply two matrixes is mentioned below

$$T = U.\ V = \max n\ [\min\ (x_{in},\ y_{nj})]$$

Here, U= x_{in} and V= y_{nj}.

By using the above rule, we obtain the fuzzy MICMAC stabilized matrix as shown in Table 12. The stabilized fuzzy matrix was obtained using MATLAB program.

To obtain the driving power of BTAs, all the row entries of the possibility of interaction are added whereas the addition of column entries provides the dependence power of BTAs. The values of row and column sum indicate the impact of each BTA towards implementation of industry 4.0 and provide a base for the management to make important decisions. Further analysis with the aid of MICMAC approach is depicted with the help of a cluster diagram. Four clusters demonstrating

Table 10
Fuzzy Direct Reachability Matrix.

Barriers	BTA1	BTA2	BTA3	BTA4	BTA5	BTA6	BTA7	BTA8	BTA9	BTA10	BTA11	BTA12
BTA1	1	0	0	0	0.75	0	0	0	0	0	0	0
BTA2	0	1	0	0	0	1	0	0	0	0	0	0
BTA3	0.5	0.25	1	0.75	0	0	0	0.25	0	0.75	0	0
BTA4	1	0.5	0	1	0.5	0	0	0	0	0	0	0
BTA5	0	0	0.75	0	1	0	0	0	0.75	0.25	0	0
BTA6	0	0	0	0	0	1	0	0	0	0	0	0
BTA7	0	0	1	0.75	0	0.25	1	0	0	1	1	0
BTA8	0	1	0	0.75	0	0.5	0	1	0.75	0.75	0	0
BTA9	0	1	0.75	1	0	0.5	1	0	1	0.75	1	0
BTA10	0	1	0	0.5	0	0.75	0	0	0	1	0	0
BTA11	0.25	0	1	0.5	0.25	0.75	0	0	0	1	1	0
BTA12	1	0	0	0.75	0	1	1	0	1	0.25	0.75	1

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9); Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

Table 11
Fuzzy MICMAC stabilized matrix.

Industry 4.0 adoption barriers	BTA1	BTA2	BTA3	BTA4	BTA5	BTA6	BTA7	BTA8	BTA9	BTA10	BTA11	BTA12	Row Total
BTA1	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA2	0	0	0	0	0	0	0	0	0	0	0	0	0
BTA3	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA4	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA5	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA6	0	0	0	0	0	0	0	0	0	0	0	0	0
BTA7	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA8	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA9	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA10	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA11	1	1	1	1	1	1	1	1	1	1	1	0	11
BTA12	1	1	1	1	1	1	1	1	1	1	1	0	11
Column Total	10	10	10	10	10	10	10	10	10	10	10	0	110

Employment Disruptions (BTA1); High Implementation Cost (BTA2); Organizational and Process Changes (BTA3); Need for Enhanced Skills (BTA4); Lack of knowledge management systems (BTA5); Lack of clear comprehension about IoT benefits (BTA6); Lack of Standards and Reference Architecture (BTA7); Lack of Internet coverage and IT facilities (BTA8); Security and Privacy Issues (BTA9). Seamless integration and compatibility issues (BTA10); Regulatory Compliance issues (BTA11); Legal and Contractual Uncertainty (BTA12).

Table 12
Prioritization of the BTAs.

Priority level	BTAs for Industry 4.0
High	• Legal and Contractual Uncertainty (BTA12)
Moderate	• Employment Disruptions (BTA1)
	• Organizational and Process Changes (BTA3)
	• Need for Enhanced Skills (BTA4)
	• Lack of knowledge management systems(BTA5)
	• Lack of Standards and Reference Architecture (BTA7)
	• Lack of Internet coverage and IT facilities (BTA8)
	• Security and Privacy Issues (BTA9)
	• Seamless integration and compatibility issues (BTA10)
	• Regulatory Compliance issues (BTA11)
Low	• High Implementation Cost (BTA2)
	• Lack of clear comprehension about IoT benefits (BTA6).

autonomous, strong dependence, linkage, and strong driver enablers were developed as shown in Fig. 4

5. Results and discussion

Through extant literature review and opinions of practitioners from industry and academia, this study identified twelve BTAs of Industry 4.0. The ISM methodology was applied to find out the relationship between the BTAs. From the model, it is observed that lack of clear comprehension about IoT benefits (BTA6) occupied the first level. Level 2 is held by high implementation cost (BTA2). Level 3 is occupied by a host of BTAs viz Employment Disruptions (BTA1), Organizational and Process Changes (BTA3), Need for Enhanced Skills (BTA4), Lack of knowledge management systems (BTA5), Lack of Standards and Reference Architecture (BTA7), Lack of Internet coverage and IT facilities (BTA8), Security and Privacy Issues (BTA9), Seamless integration and compatibility issues (BTA10), and regulatory compliance issues (BTA11). Lastly, level 4 is occupied by legal and contractual uncertainty (BTA12). BTA 12 requires changes in the policy frameworks as per the external environment and therefore holds the last level. It also signifies the uncertainty in the legal environment as they are highly dynamic. For analyzing the dependence and driving power of the BTAs of industry 4.0, fuzzy MICMAC analysis was performed. The BTAs are classified into four clusters as shown in Fig. 4.

5.1. Cluster I- autonomous BTAs

The BTAs placed in this cluster are referred to as autonomous BTAs or excluded BTAs. Plotted in the left-bottom portion of the graph these BTAs exhibit weak driving and dependence power. The BTAs falling in this cluster are considered to be out of the system, disconnected with the other elements. Further, these BTAs do not have any significant effect on the overall adoption process of Industry 4.0. The finding shows that none of the BTAs in this present study fall in the autonomous cluster. The finding supports the list of BTAs selected for the study and indicates that all the BTAs play a significant role in the Industry 4.0 adoption process.

5.2. Cluster II- dependent BTAs

The BTAs placed in this cluster are referred to as dependent or resultant barriers. Plotted in the right-bottom portion of the graph, these BTAs displays weak driving and strong dependence power. These BTAs exhibit the attributes of output variables within the entire system. Two BTAs, viz., ‘high implementation cost (BTA2)’ and ‘lack of clear comprehension about IoT Benefits (BTA6)’ are placed in this cluster. The finding indicates that BTA2 and BTA6 are highly driven and dependent on the other input variables included in the system.

5.3. Cluster III- linkage BTAs

The BTAs placed in this cluster represent the harmonized behavior of being highly influent and highly dependent. Plotted in the right-top portion of the graph these BTAs display the characteristics of strong driving and strong dependence power. A small modification in any BTA will quickly affect the other BTAs in this cluster and also influences other output BTAs (BTA2 and BTA6) in the system. In our study we find nine BTAs, viz., ‘Employment Disruptions (BTA1)’, ‘Organizational and Process Changes (BTA3)’, ‘Need for Enhanced Skills (BTA4)’, ‘Lack of knowledge management systems (BTA5)’, ‘Lack of Standards and Reference Architecture (BTA7)’, ‘Lack of Internet coverage and IT facilities (BTA8)’, ‘Security and Privacy Issues (BTA9)’, ‘Seamless integration and compatibility issues (BTA10)’, and ‘Regulatory Compliance issues (BTA11)’ falling in this cluster.

5.4. Cluster IV- driver BTAs

The BTAs placed in this cluster are referred to as driver BTAs. Plotted in the left-top portion of the graph these BTAs displays strong driving and weak dependent power. The BTAs in cluster IV acts as strong drivers of all the other BTAs. In other words, the BTAs in this cluster influences all the other BTAs in the system significantly. They act as the significant inhibitors in the adoption process. In our study ‘Legal and Contractual Uncertainty (BTA 12)’ was identified as the

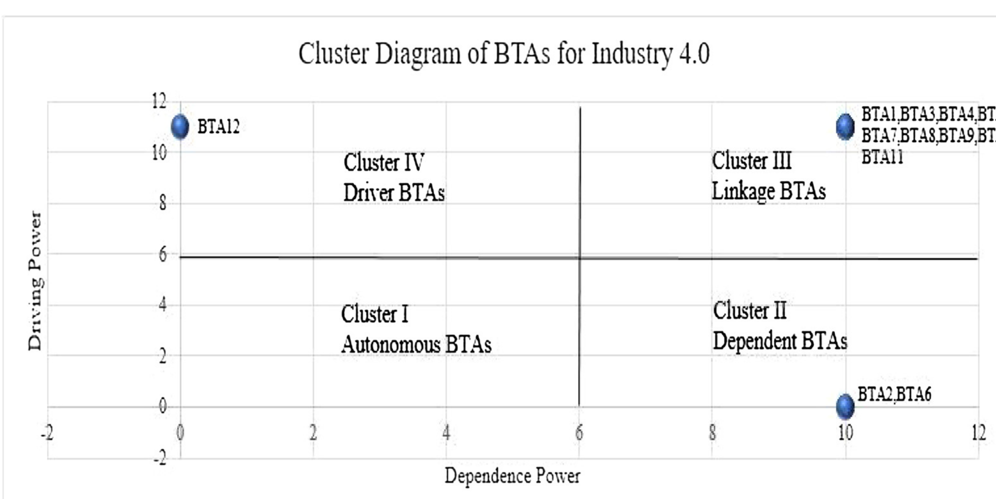

Fig. 4. Cluster diagram of BTAs to Industry 4.0.

driving barrier. The industry practitioners have to consider BTA 12 with top priority.

Table 12 shows the prioritization of the BTAs for Industry 4.0 based on the driving and dependence power.

6. Conclusions, contribution and recommendations for future research

Industry 4.0 is a revolution in manufacturing, and it brings a whole new perspective to the industry on how manufacturing can be collaborated with the latest technologies to get maximum output with minimum resource utilization. Based on literature that is available currently, the implementation constraints of industry 4.0 were identified and validated by practitioners in the manufacturing organizations. To analyze the relationships amongst the critical barriers, ISM technique using integrated with Fuzzy MICMAC analysis was used. The theoretical contributions, managerial implications and limitations of the study are discussed below.

6.1. Theoretical contributions

There is growing interest in Industry 4.0, yet there is a scarcity of systematic studies and extensive reviews of the recent research on Industry 4.0 [40]. In India, Industry 4.0 is currently perceived to be a relatively novel concept and requires more elaborative studies drawing clear definitions and interpretations [103,104]. Twelve key Industry 4.0 adoption barriers are identified using an extensive literature survey. Industry experts from manufacturing organizations further validated these barriers. The use of ISM and Fuzzy MICMAC technique provides a theoretical foundation to the identified barriers. The dependence and driver power graph developed for the BTAs reveals that we can compartmentalize the BTA's in four categories depending upon their driver power and dependence viz., linkage, autonomous, dependent and independent drivers. Independent barriers are of crucial significance in the category of barriers because they have less dependence but high driving power. The present study found that in comparison to the primary ISM model without Fuzzy MICMAC integration, the integrated model was more refined. The current research work is one of the preliminary studies that contribute to developing the theory of Industry 4.0 adoption in manufacturing organizations. The future studies should focus on finding how the impact of the driver BTA's (category IV) can be minimized as they are found to be the significant inhibiting factors in Industry 4.0 adoption. Studies in the form of case studies are suggested to identify suitable strategies for overcoming these barriers. Further studies are also required to analyze and understand how the linkage and dependent barriers perform in the manufacturing industries. Overcoming all the identified obstacles will help towards successful implementation the Industry 4.0 in the manufacturing organizations. This will facilitate the organizations for efficient integration of the business processes and activities through the cyber-physical interaction of connected elements and process innovations making the manufacturing system more flexible, economical and environmentally friendly (Wang et al., 2016, Duarte and Cruz-Machado, 2017).

6.2. Managerial implications

The findings of the study offer several implications for the industry practitioners. First, it identifies twelve Industry 4.0 adoption barriers. The practitioners can focus on these barriers and work towards minimizing their effect on the successful implementation of the Industry 4.0 in their organizations. The practitioners can achieve a high level of process integration by deploying the Industry 4.0 as an outcome of the efficient cyber-physical system and human-equipment interface [30,36] allowing for the development of smart products and processes [4]. Secondly, the study provides the relationships between the identified barriers and also categorizes them based on their driving and dependence power. This will help the practitioners and even the policymakers for a detailed understanding of the Industry 4.0 adoption process and the barriers hindering its implementation. The practitioners and policymakers may utilize the developed ISM framework to understand the inter-relationship between the barriers to build a valid and operative digital manufacturing platform. Further, this model can support practitioners to extrapolate the barriers which need to be given more attention, and their inter-relationship. It is observed from the study that "(BTA 12) legal and contractual uncertainty" barrier holds utmost importance as it directly or indirectly controls every other barrier. Industry practitioners may take required actions on the barrier to improve upon it. Academicians, on the other hand, could find themselves encouraged to categorize other such issues which are crucial in addressing these barriers. It is implied that a systematic policy on Industry 4.0 adoption process will help the organizations to achieve various sustainable benefits. The practitioners can contribute to the sustainable green practices using Industry 4.0 technologies as Industry 4.0 is believed to provide efficient resource allocation based on real-time information collected from various sources [105,106]. Industry 4.0 also offers stability to the processes through the digital management of the manufacturing process [107] improving the working conditions and providing a safe manufacturing environment to the workmen [108]. It is also implied that removing the identified hurdles in implementing the Industry 4.0 will lead to reduced costs of manufacturing [109], improved economic performance [110] and cost optimized global production networks [111].

6.3. Limitations and future directions

The present study identifies twelve barriers for Industry 4.0 adoption. However, few barriers may not have been considered which may have a significant impact in adopting Industry 4.0 in different countries context. Future studies may be conducted in different countries to investigate the existence of various barriers and evaluate the inter-relationships between them. A comparative study of the manufacturing organizations of developing and developed nations is also proposed to see the emerging differences in the perceptions of the practitioners. The weight of Fuzzy MICMAC and ISM model development are attained from a judgment of academicians and practitioners. This paper presents a subjective analysis, and any biasing by the person judging the barriers will influence the result. It is suggested to examine the causal and dependencies between the barriers by performing empirical studies based on a survey covering different industries. Further studies may use Structural Equation Modeling (SEM) to validate the developed model statistically.

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