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ScienceDirect

Procedia Computer Science 176 (2020) 2384–2393

Procedia Computer Science

www.elsevier.com/locate/procedia

24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

Industry 4.0 Implementation Challenges in Manufacturing Industries: an Interpretive Structural Modelling Approach

Ahmad Reshad Bakhtari[a]*, Vineet Kumar[a], Mohammad Maqbool Waris[b], Cesar Sanin[c], Edward Szczerbicki[d]

[a]*Sharda University, Knowledge Park III, Greater Noida 201310, India*
[b]*Adama Science and Technology University, Kebele 14 Adama, Ethiopia*
[c]*The University of Newcastle, Callaghan NSW 2308, Australia*
[d]*Gdansk University of Technology, 80-233 Gdansk, Poland*

Abstract

For the last few years, the fourth industrial revolution, known as Industry 4.0, has been a hot topic among academics. Industry 4.0 literature involves researches presenting studies related to its different aspects including challenges, opportunities, implementation and adoption. However, a detailed study of challenges and barriers towards the Industry 4.0 implementation in manufacturing industries is missing. Hence, this paper aims to study and analyze the Industry 4.0 implementation challenges in manufacturing industries based on the expert opinions and the Interpretive Structural Modelling (ISM). The ISM analysis investigates the challenges in a structural base, finds the relationships between these challenges and finally shows how challenges affect each other to uncover the root cause triggering the other challenges. The industrial practitioners and managers can then take advantage of this analysis to know which challenge acts as the main barrier towards Industry 4.0 implementation and to be focused first in order to reach a solution.

Keywords: Industry 4.0, ISM, Cyber-physical system, Challenge, Barrier.

* Corresponding author. Tel.: +91 8373923502.
E-mail address: ahmadreshadbakhtari@yahoo.com

1877-0509
10.1016/j.procs.2020.09.306

1. Introduction

In recent years, due to shortened product life cycles [1], the need for continuous innovation, the increased complexity and requirements [2] in the manufacturing environment, the industries are pushed into a new era, Industry 4.0. Industry 4.0 initially started in Germany in 2011 [3]; it is the fourth generation of the industrial revolution (see Figure 1). It was proposed by an association from industry, academia, and business in collaboration with the German government as a program to achieve a highly competitive manufacturing industry [3, 4] and to make Germany once again as the leading country in the manufacturing industry.

The motive behind each industrial revolution was to help mankind. The last three industrial revolutions arose to perform the muscle work, but Industry 4.0 arises to perform the brain function for mankind. Therefore, Industry 4.0 can be introduced as a concept that uses a set of technologies, devices, and processes to offer self-sufficient production models, able to operate with the minimum human intervention [5]. Industry 4.0 achieves this ability from the cyber-physical systems that form the basis for industry 4.0.

Cyber-physical systems allow the interaction between real and virtual world, the likes of man to machine, machine to man and machine to machine [6]. Cyber-physical systems are made up of the integration between IT systems, mechanical and electronic components connected through online networks [7] (Internet of Things) that allow the cyber-physical systems to have an integrated computational and physical capabilities [8]. Based on these capabilities cyber-physical systems enable [9]: (a) Data generation and acquisition (b) Computation and aggregation of data and (c) Decision support.

Based on these capabilities, implementation of Industry 4.0 provides new opportunities for the manufacturing industries to improve efficiency, cost reduction, and productivity [10]. Manufacturing industries can then take the advantage of these opportunities to withstand the continuous demand for innovation and shortened product life cycles, but alongside these opportunities, some challenges will hinder the Industry 4.0 implementation. Thus, manufacturing industries must know the challenges and plan accordingly to topple these challenges. Therefore, the on-hand study aims to identify these challenges and shows how to topple them. More in details, the on-hand study has the objective:

1. To identify the challenges/barriers associated with Industry 4.0 implementation in manufacturing industries, and
2. To find the hierarchy and relationship among the identified challenges.

To satisfy the first objective, based on an extent literature review challenges of Industry 4.0 implementation in manufacturing industries have been identified theoretically and validated by experts from academia and industry. Table 1 presents the challenges of Industry 4.0 implementation and their respective definition. As the research methodology this paper uses ISM analysis integrated with MICMAC analysis to analyze the hierarchy or relationship among the challenges identified from the literature. The on-hand study is structured as follows: Section 2, explains the ISM analysis application in finding the relationship among the identified challenges. Section 3, discusses the MICMAC methodology in categorization of challenges into four clusters (autonomous, dependent, linkage, and driver) and identification of the key challenges of Industry 4.0 implementation in manufacturing industries. Section 4, gives the results and discussion and finally, Section 5 represents the conclusion.

2. Interpretive Structural Modelling (ISM)

Interpretive Structural Modelling (ISM) is an individual and group learning process, which transforms unclear, ambiguous, and poorly articulated mental models of systems into well-defined graphical models called digraph [31]. ISM works based on the application of graph theory that uses the conceptual, theoretical, and computational leverage to construct a directed graph or network representation of the complex contextual relationship among a set of factors [32]. It was first proposed by Warfield in 1973 to solve and analyze the complex socioeconomic systems [33]. This methodology takes advantage of the expert's experience and knowledge to analyze and decompose a complex system into small elements and show the hierarchical relationship among these elements [34].

ISM is part of the analysis used to analyze and solve complex problems that help in decision making. Generally, researchers face difficulties in analysis of complex issues or systems, due to the involvement of a large number of elements affecting the system and interactions among these elements, e.g. the management of knowledge in an organization, which involves a large number of elements and factors associated with the knowledge sharing, knowledge creation, and knowledge acquisition [35].

Table 1. Challenges associated with Industry 4.0 implementation.

No.	Challenge	Sources	Definition
1	High initial investment cost on infrastructure	[21], [19], [18], [17], [15], [19], [11]	Industry 4.0 is based on the IoT network systems [27], which connect all the entities involved in the value creation chain, but to establish the IoT network system the manufacturing industries need to invest on their available infrastructure [17] and they see it as a big risk or challenge towards Industry 4.0 implementation [21].
2	Lack of education and skills training program	[3], [21], [20], [19], [18], [17], [16], [15], [13], [11],	With the implementation of Industry 4.0 the job and skills profiles will transform therefore the skills and qualifications of the workforce will play a key role in the success of the company [25], so the manufacturing industries need to launch and offer free education and skill training programs to their employees to align their skillset with the latest technologies used in Industry 4.0 implementation.
3	Lack of skilled workforce (Worker 4.0)	[23], [20], [19], [18], [17], [15], [19], [13], [11]	The emergence of value takes place with the combination of the tool (e.g. IoT, Big Data) and the people who operate it. As we move towards the Industry 4.0, experts and skilled workforce with specific skill sets will be required to install and maintain the tools (Technologies like IoT, Big Data, 3D printing…). Thus lack of skilled workforce can hinder the Industry 4.0 implementation.
4	Data security (Digital trust)	[23], [3], [21], [17], [16], [15], [14]	With the application of IoT in Industry 4.0, Industry 4.0 will acquire the ability of real-time operating capabilities and a massive amount of data and information flow will occur continuously. These data may include sensitive information associated with the customer and the organization. Therefore the manufacturing industries need to ensure that these data and information will be saved from unauthorized accesses, hackings, and damage.
5	Lack of digital legislation	[24], [3]	While implementing Industry 4.0, the manufacturing industries must consider the laws about data protection and liability for artificial intelligence [24]. Because the available legislations are not efficient to guarantee that while the organizations transferring data online they perform it securely, and they will not infringe privacy rules [27].
6	Lack of standardization	[22] [3], [15]	Industry 4.0 is a concept that will enable inter-company networking and integration, thus standards need to be established to stipulate the cooperation mechanisms and the information exchange [3]. In Industry 4.0 these standards are referred to as the reference architecture, which provides a framework to structure, develop, integrate and operate the technological systems (e.g. IoT, IoS) [3].
7	Lack of technology integration and compatibility	[22], [18], [15], [11]	The manufacturing industries need to upgrade their existing infrastructure into smart infrastructure that will include the integration of heterogeneous components, tools, and methods [28] (e.g. IoT, IT, IoS). But their infrastructure may not be compatible to integrate these technologies and tools.
8	Organizational constraints	[17], [15], [11]	It is clear and generally accepted that the survival, thrive and success of a company partially depends on the efforts, behaviors, and interactions of employees [29] because they are the people who carry out the mission and strategy of the company. Therefore the existing organizational culture can hinder the implementation of Industry 4.0.
9	Uncertainty of return on investment	[16], [14]	To implement Industry 4.0, the manufacturing industries need to splash and invest a large amount of money on infrastructure [17] (e.g. IoT, IT, IoS). But yet to develop clear business cases that would justify this enormous investment [16].
10	Employment disruption	[14], [13], [12],	The implementation of Industry 4.0 disrupts the employment market and when fully implemented may cause the loss of 5 million jobs globally [30]. Thus the manufacturing industries need to consider this challenge while implementing industry 4.0.
11	Expiring old business models	[3], [13]	The advancements in the disruptive technologies have increased the customers' expectations about the final product. Thus the manufacturing industries are compelled to change their existing business models to withstand the challenge posed by the increased customer expectations [13].
12	Lack of vision and leadership from top management	[14], [11]	Top management's lack of clear vision associated with the digital operations, applications and importance to the manufacturing industry [14] as well as lack of leadership/support can hinder the Industry 4.0 implementation in manufacturing industries.

Also, the direct and indirect relationship of factors, makes it difficult to understand the system structure and adds to the difficulty of dealing with such a system that its structure is not clearly defined [36]. Therefore, at first, it is needed to understand the interrelationship among the system elements, which then can help to analyze the system.

Although ISM methodology is useful to analyze complex systems by decomposing it into small elements but it has few limitations that must be taken into consideration. ISM can only act as a tool to impose the order and direction on the complex relationships among the factors [31]. The relationships among the factors depend on the group of experts' knowledge and familiarity with the system and the topic under consideration, therefore the bias and prejudges of the individual who is judging the factors may change the final result [37]. ISM methodology is an interactive learning process and it involves various steps to develop the final directed graph or digraph. In the following sections these steps are described and applied to develop the digraph and ISM model as follows.

2.1. Development of Structural Self-Interaction Matrix (SSIM)

ISM methodology is an interactive learning process and suggests the use of expert's knowledge and experience to establish the contextual relationships among the factors of the system under consideration. Thus, in this study for developing the contextual relationship among the Industry 4.0 implementation challenges in manufacturing industries, six experts-three from academia and three from industry-were consulted for this research.

The experts were questioned to establish the contextual relationship between any two challenges (i and j) and indicate the direction of the relation. The symbols (V, A, X, O) are used to show the direction of the relationship between the challenges (i and j) that will construct the Structural Self-Interaction Matrix (SSIM). The Structural Self-Interaction Matrix (SSIM) for the challenges is given in Table 2.

V: challenge *i* will influences challenge *j*;
A: challenge *j* will influence challenge *i*;
X: challenge *i* and *j* will influence each other; and
O: challenge *i* and *j* are unrelated.

Based on the Structural Self-Interaction Matrix (SSIM), Table 2 shows that the challenge 'lack of vision and leadership from top management (12)' will influence the 'high initial investment cost on infrastructure (1)' and the relationship of A is given in Table 2 for (1) and (12). Then in the case of the 'lack of education and skills training program (2)' and 'lack of skilled workforce (3)' the 'lack of skilled workforce (3)' is increased by the 'lack of education and skills training program (2)' so the relationship of V is given in Table 2 for (2) and (3). Likewise, the remaining relationships are made for the remaining challenges. In SSIM the numbers from 1 to 12 indicate the challenges as High initial investment cost on infrastructure (1), Lack of education and skills training program (2), Lack of skilled workforce (3), Digital security (4), Lack of digital legislation (5), Lack of standardization (6), Lack of technology integration and compatibility (7), Organizational Constraints (8), Uncertainty of return on investment (9), Employment disruption (10), Expiring old business model (11), Lack of vision and leadership from top management (12).

Table 2. Structural Self-Interaction Matrix (SSIM) for challenges.

Challenge	12	11	10	9	8	7	6	5	4	3	2	1
1	A	V	V	A	V	V	A	V	O	A	A	1
2	A	V	V	A	V	V	X	O	V	V	1	
3	A	V	X	X	V	V	V	V	V	1		
4	A	O	O	V	O	V	A	X	1			
5	A	V	V	A	V	V	A	1				
6	A	V	V	X	O	A	1					
7	A	V	V	A	O	1						
8	A	V	V	O	1							

9	A	V	V	1
10	A	V	1	
11	A	1		
12	1			

2.2. Reachability Matrix

In this step a binary matrix [31] is developed from the Structural Self-Interaction Matrix (SSIM), known as the initial reachability matrix by replacing V, A, X, O with 1 and 0 as per the rules. The rules for the replacing of 1 and 0 are as follows:

- If the (*i,j*) entry in the SSIM is V, then the (*i,j*) in the reachability matrix is replaced with 1 and the (*j,i*) entry is replaced with 0.
- If the (*i,j*) entry in the SSIM is A, then the (*i,j*) in the reachability matrix is replaced with 0 and the (*j,i*) entry is replaced with 1.
- If the (*i,j*) entry in the SSIM is X, then the (*i,j*) in the reachability matrix is replaced with 1 and the (*j,i*) entry is replaced with 1.
- If the (*i,j*) entry in the SSIM is O, then the (*i,j*) in the reachability matrix is replaced with 0 and the (*j,i*) entry is replaced with 0.

By employing the rules, an initial reachability matrix for the challenges is derived as shown in Table 3. Then by checking the transitivity, the final reachability matrix is obtained after the incorporation of the transitivity. Table 4, shows the final reachability matrix and the driving power and dependence for each challenge. The driving power of a challenge states for the total number of challenges (including itself), which it may influence. The dependence of a challenge states for the total number of challenges (including itself), which may influence it.

Table 3. Initial reachability matrix for challenges.

Challenge	12	11	10	9	8	7	6	5	4	3	2	1	Drive power
1	0	1	1	0	1	1	0	1	0	0	0	1	6
2	0	1	1	0	1	1	1	0	1	1	1	1	9
3	0	1	1	1	1	1	1	1	1	1	0	1	10
4	0	0	0	1	0	1	0	1	1	0	0	0	4
5	0	1	1	0	1	1	0	1	1	0	0	0	6
6	0	1	1	1	0	0	1	1	1	0	1	1	8
7	0	1	1	0	0	1	1	0	0	0	0	0	4
8	0	1	1	0	1	0	0	0	0	0	0	0	3
9	0	1	1	1	0	1	1	1	0	1	1	1	9
10	0	1	1	0	0	0	0	0	0	1	0	0	3
11	0	1	0	0	0	0	0	0	0	0	0	0	1
12	1	1	1	1	1	1	1	1	1	1	1	1	12
Dependence	1	11	10	5	6	8	6	7	6	5	4	6	

Table 4. Final reachability matrix for challenges.

Challenge	12	11	10	9	8	7	6	5	4	3	2	1	Drive power
1	0	1	1	0	1	1	1*	1	1*	1*	0	1	9
2	0	1	1	1*	1	1	1	1*	1	1	1	1	11
3	0	1	1	1	1	1	1	1	1	1	1*	1	11

4	0	1*	1*	1	1*	1	1*	1	1	0	0	0	8
5	0	1	1	1*	1	1	1*	1	1	1*	0	0	9
6	0	1	1	1	1*	1*	1	1	1	1*	1	1	11
7	0	1	1	1*	0	1	1	1*	1*	1*	1*	1*	10
8	0	1	1	0	1	0	0	0	0	1*	0	0	4
9	0	1	1	1	1*	1	1	1	1*	1	1	1	11
10	0	1	1	1*	1*	1*	1*	1*	1*	1	0	1*	10
11	0	1	0	0	0	0	0	0	0	0	0	0	1
12	1	1	1	1	1	1	1	1	1	1	1	1	12
Dependence	1	12	11	9	10	10	10	10	10	10	6	8	

2.3. Level Partitioning

To perform the level partitioning, the reachability and antecedent set for each challenge are derived from the final reachability matrix. For a particular challenge, the reachability set consists of the challenge itself and the other challenges that it may influence. The antecedent set consists of the challenge itself and the other challenges that may influence it. Afterward, the intersection set for all of the challenges is derived from the reachability and antecedent sets. For the challenge that the reachability and the intersection sets are the same is identified as the top-level challenge in the ISM hierarchy that cannot influence any other challenge above their level. As soon as the top-level challenge is identified, it is removed from the remaining challenges. As shown in Table 5 that challenge 'Expiring old business models (11)' is identified to be at level 1. Therefore, it will be demonstrated at the top of the ISM model. The level partitioning is an iterative action and will continue until the level of each challenge is identified. These levels then will help to build the directed graph or digraph and the final ISM model. The reachability set, antecedent set, intersection set and the level for each challenge are shown in Table 5.

Table 5. Level partition for challenges.

Challenge	Reachability set	Antecedent set	Intersection set	Level
1	1,3,4,5,6,7,8,10,11	1,2,3,6,7,9,10,12	1,3,6,7,10	
2	1,2,3,4,5,6,7,8,9,10,11	2,3,6,7,9,12	2,3,6,7,9	
3	1,2,3,4,5,6,7,8,9,10,11	1,2,3,5,6,7,8,9,10,12	1,2,3,5,6,7,8,9,10	
4	4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,9,10,12	4,5,6,7,9,10	
5	3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,9,10,12	3,4,5,6,7,9,10	
6	1,2,3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,9,10,12	1,2,3,4,5,6,7,9,10	
7	,1,2,3,4,5,6,7,9,10,11	1,2,3,4,5,6,7,9,10,12	1,2,3,4,5,6,7,9,10	
8	3,8,10,11	1,2,3,4,5,6,8,9,10,12	3,8,10	
9	1,2,3,4,5,6,7,8,9,10,11	2,3,4,5,6,7,9,10,12	2,3,4,5,6,7,9,10	
10	1,3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,8,9,10,12	1,3,4,5,6,7,8,9,10	
11	11	1,2,3,4,5,6,7,8,9,10,11,12	11	Level 1
12	1,2,3,4,5,6,7,8,9,10,11,12	12	12	
1	1,3,4,5,6,7,8,10	1,2,3,6,7,9,10,12	1,3,6,7,10	
2	1,2,3,4,5,6,7,8,9,10	2,3,6,7,9,12	2,3,6,7,9	
3	1,2,3,4,5,6,7,8,9,10	1,2,3,5,6,7,8,9,10,12	1,2,3,5,6,7,8,9,10	
4	4,5,6,7,8,9,10	1,2,3,4,5,6,7,9,10,12	4,5,6,7,9,10	
5	3,4,5,6,7,8,9,10	1,2,3,4,5,6,7,9,10,12	3,4,5,6,7,9,10	
6	1,2,3,4,5,6,7,8,9,10	1,2,3,4,5,6,7,9,10,12	1,2,3,4,5,6,7,9,10	

7	1,2,3,4,5,6,7,9,10	1,2,3,4,5,6,7,9,10,12	1,2,3,4,5,6,7,9,10	Level 2
8	3,8,10	1,2,3,4,5,6,8,9,10,12	3,8,10	Level 2
9	1,2,3,4,5,6,7,8,9,10	2,3,4,5,6,7,9,10,12	2,3,4,5,6,7,9,10	
10	1,3,4,5,6,7,8,9,10	1,2,3,4,5,6,7,8,9,10,12	1,3,4,5,6,7,8,9,10	Level 2
12	1,2,3,4,5,6,7,8,9,10,12	12	12	
1	1,3,4,5,6	1,2,3,6,9,12	1,3,6	
2	1,2,3,4,5,6,9	2,3,6,9,12	2,3,6,9	
3	1,2,3,4,5,6,9	1,2,3,5,6,9,12	1,2,3,5,6,9	
4	4,5,6,9	1,2,3,4,5,6,9,12	4,5,6,9	Level 3
5	3,4,5,6,9	1,2,3,4,5,6,9,12	3,4,5,6,9	Level 3
6	1,2,3,4,5,6,9	1,2,3,4,5,6,9,12	1,2,3,4,5,6,9	Level 3
9	1,2,3,4,5,6,9	2,3,4,5,6,9,12	2,3,4,5,6,9	
12	1,2,3,4,5,6,9,12	12	12	
1	1,3	1,2,3,9,12	1,3	Level 4
2	1,2,3,9	2,3,9,12	2,3,9	
3	1,2,3,9	1,2,3,9,12	1,2,3,9	Level 4
9	1,2,3,9	2,3,9,12	2,3,9	
12	1,2,3,9,12	12	12	
2	2,9	2,9,12	2,9	Level 5
9	2,9	2,9,12	2,9	Level 5
12	2,9,12	12	12	
12	12	12	12	Level 6

2.4. ISM Model

In the last steps, by using the final reachability matrix, the structure model is developed. The arrow pointing from a challenge (*i*) to challenge (*j*) shows the existence of the relationship between the two challenges. After the drawing of all relationships a graph is achieved, called a directed graph or digraph. By removing the transitivity links the digraph is converted into the ISM model as shown in Figure 1. Figure 1 shows that the 'lack of vision and leadership from top management' acts as the main barrier as it comes at the bottom of the ISM hierarchy and influences all other challenges. Figure 1 shows the details of the full ISM model for the Industry 4.0 implementation challenges in manufacturing industries.

3. Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) Analysis

To analyze the driving and dependence power of the challenges, MICMAC analysis is used. In MICMAC analysis the challenges are categorized into four clusters based on their driving and dependence power as shown in Figure 2. The first cluster is called Autonomous cluster and is consists of the factors that have weak driving and weak dependence power, but none of the challenges come in this cluster. The second cluster is called Dependent cluster and is consist of factors that have weak driving power and strong dependence power, the 8th and 11th challenges come in this cluster. The third cluster is called Linkage cluster and is consist of factors that have strong driving and dependence power, the 1, 3, 4, 5, 6, 9, and 10 challenges come in this cluster. The fourth cluster is called Driver cluster and is consists of the factors that have strong driving power but weak dependence power, 2nd and 12th challenges come in this cluster. Based on the MICMAC analysis, the challenge of having a very strong driving power and very weak dependence power is called as the key challenge. In this study, the 2nd and 12th challenges are the key challenges as shown in Figure 2.

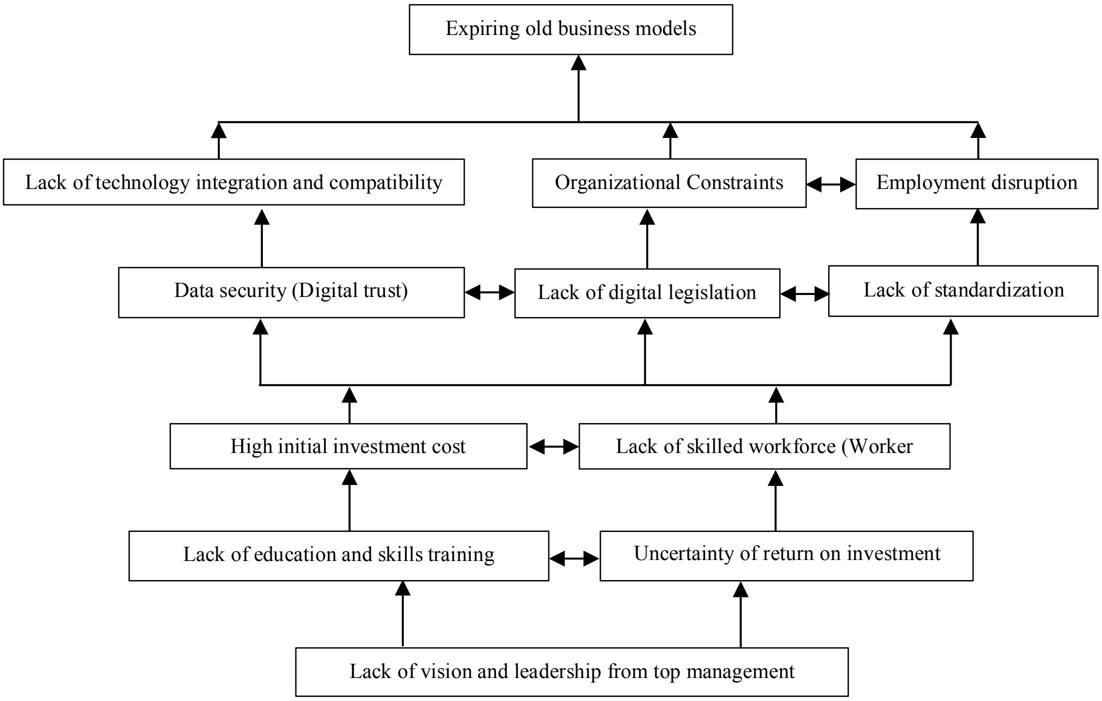

Fig. 1. Interpretive structural model (ISM) showing the levels of Industry 4.0 implementation challenges

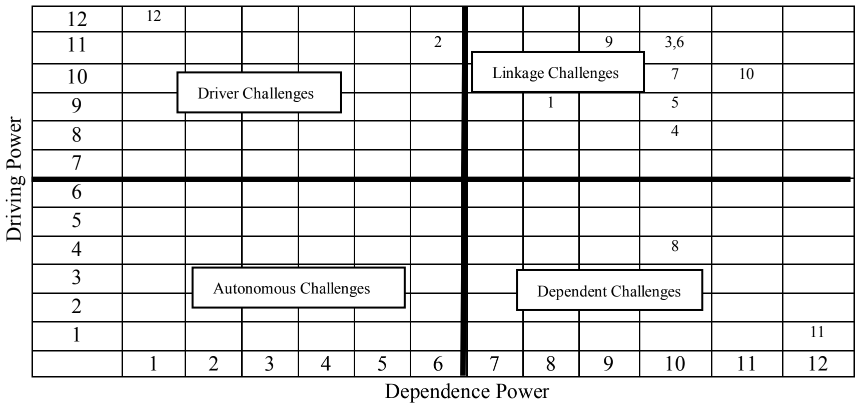

Fig. 2. Driving power and dependence diagram of challenges for MICMAC analysis

4. Results and Discussion

The on-hand study has highlighted some major challenges of Industry 4.0 implementation in manufacturing industries and put into an ISM model to analyze and identify the relationship and interaction between the challenges. The MICMAC analysis provides some valuable and significant insights on the interdependencies among the challenges and their relative importance. As shown in Figure 2, the 12th and 2nd challenge have high driving power and the low dependence power, thus observed that they act as the main challenges and are indicated as the key challenges. The 11th and 8th challenge have low driving power, but high dependence power, therefore they are indicated as the dependent and low affecting challenges. The other challenges (1, 3, 4, 5, 6, 7, 9, and 10) have high driving power as well as high dependence power, thus they are indicated as the linking challenges and are unstable that any action on these challenges will affect others and also have a feedback on themselves.

As shown in figure 1, the 'Lack of vision and leadership from top management (12)' challenge forms the base of the ISM model and the main challenge towards Industry 4.0 implementation in manufacturing industries and the 'Expiring old business models (11)' challenge forms the top of the ISM model and lowest affecting challenge associated with the Industry 4.0 implementation in manufacturing industries.

5. Conclusion

Industrial revolutions in the past have served as major turning points in history; they have affected almost all the industrial sectors and altered every aspect of their functions and operations. Industry 4.0 is a new phenomenon and stands for the fourth industrial revolution. The employment of disruptive technologies like IoT, IoS, Big Data, etc. in Industry 4.0 will help to increase the efficiency and productivity as well as the end product customization. Therefore, the manufacturing industries need to implement Industry 4.0, to maintain their competitiveness in today's dynamic market. The implementation of Industry 4.0 will bring deep changes in manufacturing industries. Thus, the manufacturing industries will face lots of challenges while implementing Industry 4.0.

This study developed the ISM model integrated with MICMAC analysis for the interactions and relationships among the challenges and showed the hierarchy of the challenges as well as identified the key challenges that will hinder Industry 4.0 implementation in manufacturing industries. The proposed ISM model can help the industrial practitioners and managers with a more realistic representation of the challenges in the course of Industry 4.0 implementation in manufacturing industries and can help them in the decision making process. However, the ISM analysis has several flaws, because it only analyzes the interactions and relationships among the challenges. In future research, one can apply the Structural Equation Modelling (SEM) to statistically evaluate the present model and can perform a comparative study of the identified challenges. Therefore, future research can be directed to evaluate the validity of the developed ISM model by employing the SEM technique.

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