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Evaluating Industry 4.0 Implementation Challenges Using Interpretive Structural Modelling and Fuzzy-Analytic Hierarchy Process

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Abstract

The fourth industrial revolution known as Industry 4.0 is reshaping and evolving the way industries produce products and individuals live and work therefore, gaining massive attraction from academia, business and politics. The manufacturing industries are optimistic regarding the opportunities Industry 4.0 may offer such as, improved efficiency, productivity and customization. The present research contributes to the Industry 4.0 literature by identifying, modelling, analyzing and prioritizing the challenges in implementing Industry 4.0 in manufacturing industries. In doing so, the paper first introduces the interpretive structural modelling (ISM) to develop the hierarchical relationships among the challenges and analyzes their mutual interactions. Further, 'Matrice d'Impacts Croises Multiplication Appliquee aun Classement' (MICMAC) analysis is used to categorize the challenges into four categories namely, autonomous, driver, dependent and linkage based on their driving power and dependence power. Moreover, fuzzy-analytic hierarchy process (F-AHP) methodology is used to prioritize the challenges based on three criteria; driving power, dependence power and change management. The hierarchical model developed through ISM methodology shows that "lack of vision and leadership from top management (C12), lack of skills training program and education (C2) and uncertainty of return on investment (C9)" are the major challenges in implementing Industry 4.0 in manufacturing industries. The findings of F-AHP analysis suggests that "lack of vision and leadership from top management (C12), lack of skilled workforce (C3), lack of skills training program and education (C2) and uncertainty of return on investment (C9)" are some of the major challenges of implementing Industry 4.0. Finally, the obtained results show how challenges affect other so that to uncover the root cause triggering the other challenges. The industrial practitioners and managers can then take advantage of these analyzes to know which challenge acts as the main barrier in implementing Industry 4.0 and to be focused first in order to reach a solution.

Keywords: ISM, Fuzzy-AHP, Challenges, Industry 4.0, Barriers

1. Introduction

1.1. Industrial Revolutions

The manufacturing industries throughout the history has experienced three revolutionary phases, from the hand production systems into mechanized systems during the 18th century and the today's computer-aided and digitized manufacturing systems (see Figure 1). Each of these phases are marked as the industrial revolution and since then, the world has gone through a drastic change. Due to this change, people all around the world today live healthier, longer, and much more productive lives. Thanks to the manufacturing because it has been one of the key drivers in creating and progressing innovations and technology.

The invention of steam engine in Britain between the years 1760 to 1830; triggered the 1st industrial revolution in human history that served as the transition period of manufacturing processes from hand production systems to mechanized production systems. The main cause behind the industrialization was the change in power sources. The steam engine powered by coal kept industries and factories producing faster and efficient than before by providing continuous mechanical energy. By employing mechanical energy generated by the steam engines, the factories and industries became mechanized which in turn replaced the manual work with the machines fueled by mechanical energy [1]. Due to this fundamental change in industry, the productivity and efficiency have seen a tremendous increase which ultimately enabled mass production.

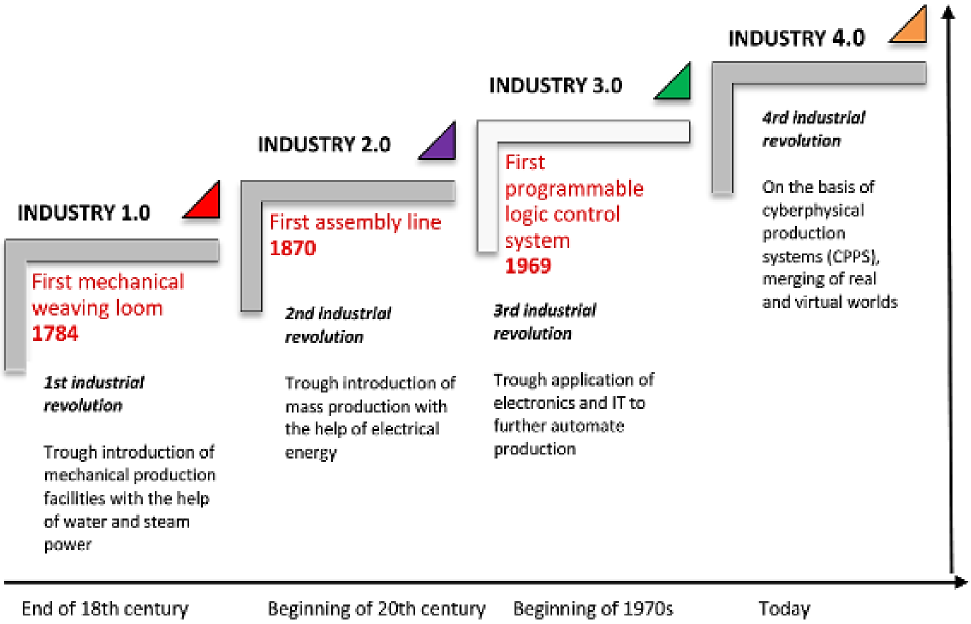

Figure 1. The last three industrial revolutions and Industry 4.0 [6]

In the late 19th century the technological advances in iron and steel production, division of labor, invention of light bulb, Henry Ford’s assembly line that altered the production methods and the way how products were produced before, and advances in transportation like trains that reduced time taken to travel between cities and the introduction of cars that increased the mobility inside cities paved the way towards the 2nd industrial revolution. In the 2nd industrial revolution, the power source shifted from coal to electricity, and with the electricity as an energy source combined with the technological advances such as trains, cars, assembly line and light bulb, mass production started in the latter half of the nineteenth century [2].

The 3rd industrial revolution was triggered with the invention and advancement of micro-controllers, robots [3], transistors, and computer. The 3rd industrial revolution started in the mid-20th century with the introduction of automation and digitization to manufacturing industries. The combined application of computer and automation in manufacturing industry, enabled the integration of computers into the planning and production processes with the goal of controlling the entire production process, which in turn introduced Computer Integrated Manufacturing (CIM). All the technological advances and developments have made the last three industrial revolutions possible and led to the present conditions in the manufacturing industries.

1.2. Industry 4.0

The latest Industrial revolution branded as the Industry 4.0, first came into existence when the German government introduced it as the fourth industrial revolution at the Hanover Messe in the year 2011 [4]. The German government proposed it as a program to achieve a highly competitive manufacturing industry [4, 5] and to make Germany once again as the leading country in the manufacturing industry. Industry 4.0 soon attracted the attentions of the researchers and scientists from around the globe, leading to the discussions over it as an opportunity or threat. There are arguments that it will bring new opportunities as well as challenges [7] for the manufacturing industries and society at a large scale.

Industry 4.0 integrates the physical/real and digital/virtual worlds, enabling several industrial advancements that will allow enhancements associated with efficiency and productivity for industries implementing this new concept. Beside the increase in productivity and efficiency Industry 4.0 reveals a change of focus from mass production to mass customization which is focused towards individualized customer preferences and requirements. The German government's Industry 4.0 initiative inspired other countries to launch similar strategies [8] to remain competitive in the manufacturing industry and among these countries, USA has invested the highest amount to pave the way towards the Industry 4.0 or as they call it smart manufacturing [8, 9]. Some of the similar initiatives taken by other countries are listed below:

- *Advanced Manufacturing Partnership* of the United States of America in 2011,
- *Future of Manufacturing* of United Kingdom in 2013,
- *The New Industrial France* of France in 2013,
- *Innovation in Manufacturing 3.0* of South Korea in 2014,
- *Made in China 2025 and Internet Plus* of China in 2015
- *Super Smart Society* of Japan in 2015

The advancements in disruptive technologies such as IoT, Computer, Augmented Reality, Cyber Physical Systems (CPS), Big Data, Digital Manufacturing, Network Communication and other technologies [10] affect both products and production processes, enabling the increase in productivity and efficiency and helping in realization of the Industry 4.0 dream into reality.

With the ability to continuously monitor [11] and control the products and real time data processing due to new advancements in information technology (IT), Industry 4.0 will be adopted by industries very soon [12] and the shift from current industrial stage to Industry 4.0

will be inevitable. This shift has various challenges/barriers and opportunities because implementation of Industry 4.0 will bring deep changes to the manufacturing industries and transforms all the activities within them [13]. Thus, the manufacturing industries will face lots of challenges while implementing Industry 4.0.

Kiel [14], Müller and Voigt [15], Erol [16], and Adolph [17] studied the Industry 4.0 and identified two challenges that hinder its implementation; the lack of skilled workforce and the need to reeducate employees with the new skills so that they can adapt to the changing work environment. In addition, a number of sources [14, 15, 16, 18, 19] have concluded that the lack of financial resources hinders its implementation as well. Beside these challenges, Müller and Voigt [15] and Kiel [14] also found that lack of technology integration and compatibility, which is the technical transformation and modernization of manufacturing facilities and assets, will hinder the Industry 4.0 implementation.

Due to the advantages (increase in productivity, safety, efficiency, customization and sustainability) that the implementation of Industry 4.0 can bring, the interest of manufacturing industries in its implementation is increasing [20, 21] and the reason behind this interest comes from their eagerness of being competitive in today's dynamic market [13]. Therefore, they have to prepare themselves for its implementation and to do so, they need to know all the features and different aspects of Industry 4.0. Besides knowing its features, they must also identify its implementation challenges and know how these challenges affect each other and which one of them will have the most impact so that strategic decisions could be taken accordingly to topple these challenges. Hence, this paper focuses on Industry 4.0 implementation challenges in manufacturing industries for formulating a structural relationship using Interpretive Structural Modelling (ISM) analysis and then to prioritize the identified challenges. The prioritization of the Industry 4.0 implementation challenges using fuzzy-analytic hierarchy process (Fuzzy-AHP) in the manufacturing industries is a prominent contribution of the on-hand study.

The rest of the paper is structured as follows: Section 2, describes the ISM analysis integrated with MICMAC analysis in finding the hierarchy and relationship among the identified challenges and classification of challenges. Section 3, explains the fuzzy-AHP and its application in prioritization of the Industry 4.0 implementation challenges. Section 4, gives the managerial implications of the study. Section 5, presents the results and discussion and section 6, describes the conclusion, limitation of the on-hand study and scope for further research.

2. Research Methodology

The rapid change in market condition, the increase in customer demands, and the need for continuous innovation [22] force the manufacturing industries to improve their productivity and flexibility. For improving the productivity and efficiency, industrial managers need to use disruptive technologies and implement the latest advancements to maintain their competitiveness in the market, else they will be destined to annihilation. But while implementing these advancements the industrial managers may face some challenges, therefore at first, they must identify these challenges and find the ways to overcome them.

The objective of this study is to prioritize the challenges in implementation of Industry 4.0 in manufacturing industries. Initially, based on a comprehensive literature review, the relevant challenges of Industry 4.0 implementation are identified and validated by experts from academia and industry. In this study twelve challenges have been identified that can hinder implementation of Industry 4.0 in manufacturing industries and are described as follows:

1. *High Initial Investment Cost on Infrastructure:* Industry 4.0 is based on the IoT network systems [23], 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 [14] and they see it as a big risk or challenge towards Industry 4.0 implementation [24].
2. *Lack of Education and Skills Training Program*: 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)*: 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)*: With the application of IoT, 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*: While the industries are implementing Industry 4.0, they must consider the laws about data protection and liability for artificial intelligence [26]. 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*: 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 [4]. 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) [4].
7. *Lack of Technology Integration and Compatibility*: The manufacturing industries need to upgrade their existing infrastructure into smart infrastructure that will include the integration of heterogeneous components, tools, and methods [10] (e.g. IoT, IT, IoS). But their infrastructure may not be compatible to integrate these technologies and tools.

8. *Organizational Constraints*: 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 [28] 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*: The manufacturing industries need to transform their infrastructure in order to implement Industry 4.0 therefore, they need to splash and invest a large amount of money on infrastructure [29] (e.g. IoT, IT, IoS). But yet to develop clear business cases that would justify this enormous investment [30].
10. *Employment Disruption*: The implementation of Industry 4.0 disrupts the employment market and when fully implemented may cause the loss of 5 million jobs globally [31]. Thus, the manufacturing industries need to consider this challenge while implementing industry 4.0.
11. *Expiring Old Business Models*: 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 [32].
12. *Lack of Vision and Leadership from Top Management*: Top management's lack of clear vision associated with the digital operations, applications and importance to the manufacturing industry [33] as well as lack of leadership/support can hinder the Industry 4.0 implementation in manufacturing industries [19].

ISM technique is used to show the interrelationship and construct the hierarchy among the twelve challenges. Furthermore, the MICMAC analysis is integrated with the interpretive structural modelling to categorize the challenges based on their driving power and dependence power obtained from the ISM analysis. Lastly, Fuzzy-AHP is applied to prioritize the challenges based on the criteria: driving power, dependence power and change management required.

2.1. Interpretive Structural Modelling

Interpretive structural modelling or shortly ISM is primarily an individual or a group learning process. It was first developed and introduced to analyze the problems regarding complex socioeconomic systems [34]. It is used to convert ambiguous, complex, and inexpertly articulated models of systems having various factors and criteria into graphical, easy understandable, clear, and visible models [35]. It works based on the application of graph theory to create a model that show the hierarchical relationship or complex contextual relationship among a set of variables [36]. The final developed model is generally called directed graph or shortly a digraph.

Systems are made up of elements and a system with large number of elements makes it difficult to be analyzed and understood. It is due to the interactions and relationships (direct or indirect) among the systems' elements. ISM comes handy while dealing with these kinds of complex systems. To decompose and analyze the elements of a complex system into small elements and show the hierarchical relationship among them, the ISM methodology takes the advantage of experts' opinion and knowledge [37]. But one thing should be kept in mind that the experts who take part in ISM analysis must have enough experience and knowledge of the problem (system) under consideration. Otherwise, the developed ISM-based model might suffer from experts' inaccurate judgement of variables.

ISM comes into action when methodical, orderly and rational thinking, are used to approach a problem consisting a large number of elements. It helps to find the direction and order of the relationships among a set of elements [35]. From this definition, ISM analysis can be understood as a tool, which can only impose order and direction to the interactions (relationships) of a system's factors under consideration. Ghobakhloo [38] used the ISM analysis to model the critical sustainability functions of Industry 4.0 and identified that "human resource development function" forms the basis for the development of other sustainability functions of Industry 4.0. By employing ISM technique, Mohammad [39] performed a study to investigate relationship among lean enablers in SMEs in Kurdistan Region of Iraq (KRI-SMEs) and identified the "awareness and commitment of the top management" as the main enabler of lean in KRI-SMEs. Devi, et al. [40] used the ISM technique in categorization of the technological enablers of Industry 4.0 implementation in Indian manufacturing industry. Moreover, there are numerous applications of ISM methodology that can be seen in literature [41, 42, 43, 44, 45].

ISM analysis is primarily an interactive learning method that involves several steps to develop the final model or digraph. Therefore, at first it will be better to give an insight to the steps involved. The steps involved are [46]:

1. Identification of the factors for the system under consideration.
2. Establishment of the contextual relationship between the identified factors.
3. Development of Structural Self-Interaction Matrix (SSIM) that represents the mutual relationships among factors.
4. Development of Initial Reachability matrix on the basis of SSIM and then check for transitivity and final Reachability matrix is derived. Transitivity means that if factor A affects factor B and factor B affects factor C, then factor A indirectly affects factor C.
5. Level partitioning of the Final Reachability matrix FRM.
6. Development of directed graph or digraph on the basis of (FRM).
7. Replacement of factor nodes with statements to convert the resultant directed graph into a final ISM model.
8. The last step is checking for conceptual inconsistency in the developed ISM-based model and then incorporating necessary modifications.

2.1.1. Establishment of Contextual Relationship among the Challenges

By using an extent literature review, twelve challenges towards Industry 4.0 implementation in manufacturing industries are identified. After the identification of challenges, the upcoming step is establishment of a contextual relationship among these challenges. In this analysis a contextual relationship of ‘influences it’ is used to define and show the relationships among the identified challenges and it means that one challenge influences other challenge. By applying this principle and using experts’ opinion, a contextual relationship among the challenges is developed.

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

ISM methodology is an interactive learning process and suggests the use of expert’s knowledge and experience. Therefore, establishment of contextual relationships for the challenges will depend on the usage of experts’ opinion. In this study for establishing the contextual relationships among the challenges, six experts-three academic experts and three industrial professionals- were consulted for this research.

The experts were questioned to establish the contextual relationship among the challenges (i and j) and state in which direction they will influence each other. To make this process easy and understandable the four symbols (V, A, X, O) are used. These symbols show in which direction the challenges (i and j) influence each other and on the basis of these symbols the SSIM is constructed. Table 1 shows the SSIM for the identified challenges.

V: The (i) challenge will influence the (j) challenge;
A: The (j) challenge will influence (i) challenge;
X: Both challenges (i and j) will influence each other mutually; and
O: None of the challenges (i and j) will influence each other.

Based on the SSIM, Table 1 shows that the challenge “lack of vision and leadership from top management (12)” will influence the challenge “high initial investment cost on infrastructure (1)” therefore in Table 1 a relationship of A is given for (1) and (12). Further, it is stated the “lack of skilled workforce (3)” is influenced by the “lack of education and skills training program (2)” therefore in Table 1 a relationship of V is given for (2) and (3). The remaining relationships for the remaining challenges are made accordingly. 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 1. 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											

2.1.3. Reachability Matrix

In the fourth step on the basis of the SSIM a binary matrix [37], which is called initial reachability matrix, is developed. The symbols V, A, X, O in the initial reachability matrix are replaced with 1 and 0 as per the rules describe below:

- For the V, the (i,j) entry is replaced with 1 and the (j,i) entry is replaced with 0.
- For the A, the (i,j) entry is replaced with 0 and the (j,i) entry is replaced with 1.
- For the X, (i,j) and (j,i) entries are replaced with 1.
- For the O, the (i,j) and (j,i) entries are replaced with 0.

Table 2 shows the initial reachability matrix for the challenges after employing the above rules. Then by checking the transitivity as described in the sixth step of the ISM analysis and incorporating the transitivity rule the final reachability matrix is obtained. Table 3, shows the final reachability matrix and the driving and dependence power for all the 12 challenges. The driv3 power of a challenge is the sum of challenges (consisting itself) that it might influence. The dependence power of a challenge is the sum of challenges (consisting itself) that might influence it.

Table 2. 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 3. 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	

2.1.4. Level Partitioning

In the fifth step of the ISM analysis, it is needed to perform the level partitioning. Level partitioning is the process of leveling challenges into different levels. To do this, reachability and antecedent set are required to be derived from the final reachability matrix. Reachability set contains all the challenges (consisting itself) that it might influence and the antecedent set contains all the challenges (consisting itself) that might influence it. Afterward, the intersection set is formed from reachability and antecedent sets.

For a particular challenge that both the sets (reachability and the intersection) have the same numbers and are identical, is identified to be the top-level challenge in the ISM model. It means that this challenge cannot influence any other challenge above its level. Then, the identified top-level challenge is removed from the sets (reachability, intersection and antecedent) in order to find the challenge/challenges in the next level. As shown in Table 4-itration 1 that challenge “Expiring old business models (11)” is identified as the challenge at level 1 and therefore it will be demonstrated at the top of the ISM hierarchy. Level partitioning is an iterative and repetitive action and will continue till all the levels in the ISM hierarchy are identified. The same procedure will be used to find the levels of all other challenges and eventually, on the basis of identified levels and final reachability matrix, a directed graph or digraph is constructed. Table 4 shows the reachability set, antecedent set, and intersection set for all the challenges and the following iterations show level partitioning process.

Table 4. Level partition for challenges-Iteration 1.

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	
		Iteration 2		
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	
		Iteration 3		
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	
		Iteration 4		
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	
		Iteration 5		
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	
		Iteration 6		
12	12	12	12	Level 6

2.1.5. Development of Directed Graph (Digraph)

By using Table 5, a directed graph which includes the transitive links is developed (see Figure 2). After the construction of the digraph, the indirect or transitive links are removed to obtain a final digraph, as shown in Figure 3. In digraph, the level-1 challenge will be placed at top and level-2 challenge/challenges will be positioned below the level-1 challenge. The same procedure will be followed till the final digraph is obtained.

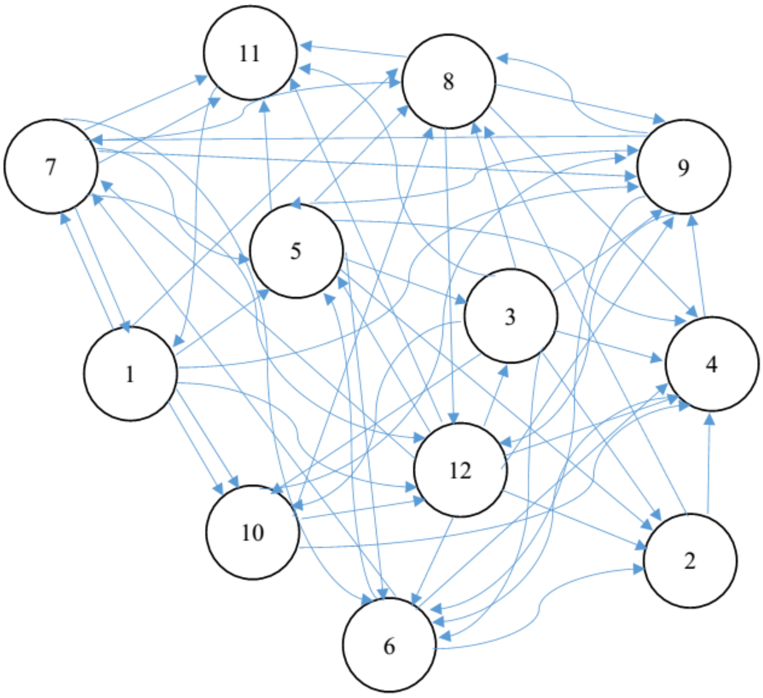

Figure 2 Relationship between challenges without ISM analysis

Table 5. Overall 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	Level 4
2	1,2,3,4,5,6,7,8,9,10,11	2,3,6,7,9,12	2,3,6,7,9	Level 5
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	Level 4
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	Level 3
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	Level 3

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	Level 3
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	Level 2
8	3,8,10,11	1,2,3,4,5,6,8,9,10,12	3,8,10	Level 2
9	1,2,3,4,5,6,7,8,9,10,11	2,3,4,5,6,7,9,10,12	2,3,4,5,6,7,9,10	Level 5
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	Level 2
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	Level 6

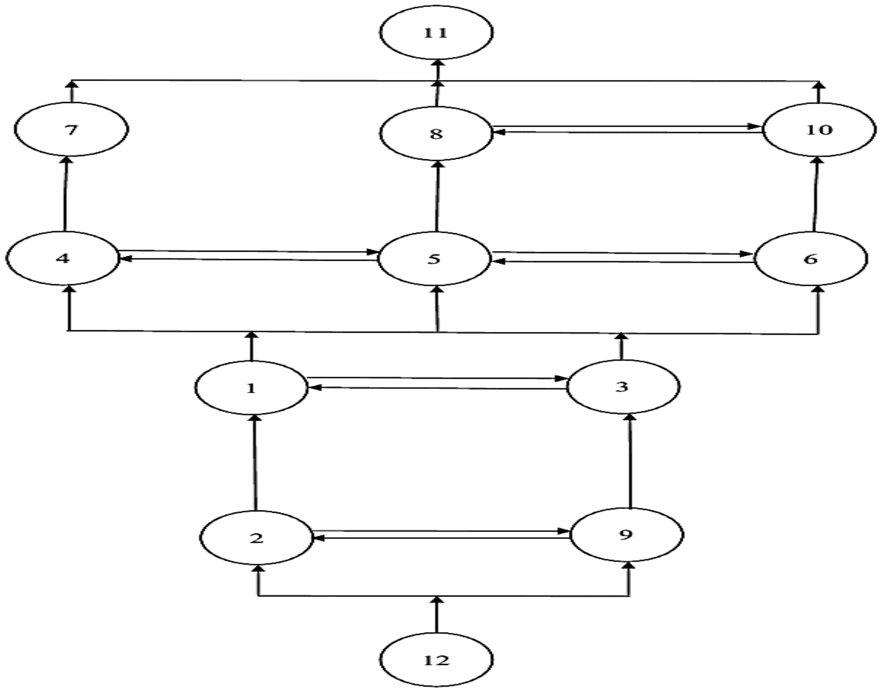

Figure 1. Final directed graph

2.1.6. ISM Model

Next, by using the final digraph, 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. The ISM model is obtained by removing the transitivity links as stated in 6th step of the ISM methodology and by writing the statements in place of the elements' nodes in the digraph (see Figure 4). Figure 4 shows that the challenge "lack of vision and leadership from top management" comes at the bottom of the ISM model and the other challenges are placed above it. This means that this challenge acts as the main barrier and it affects/influences all other challenges above its level therefore, it is identified as the key challenge against implementing Industry 4.0 in manufacturing industries. Figure 4 shows that the challenges "lack of education and skills training program" and "uncertainty of return on investment" are positioned at the next level, above the "lack of vision and leadership from top management" and the arrow pointing from down to up shows that they are influenced by the down-level challenge. Furthermore, Figure 4 depicts that the challenge "expiring old business models" is

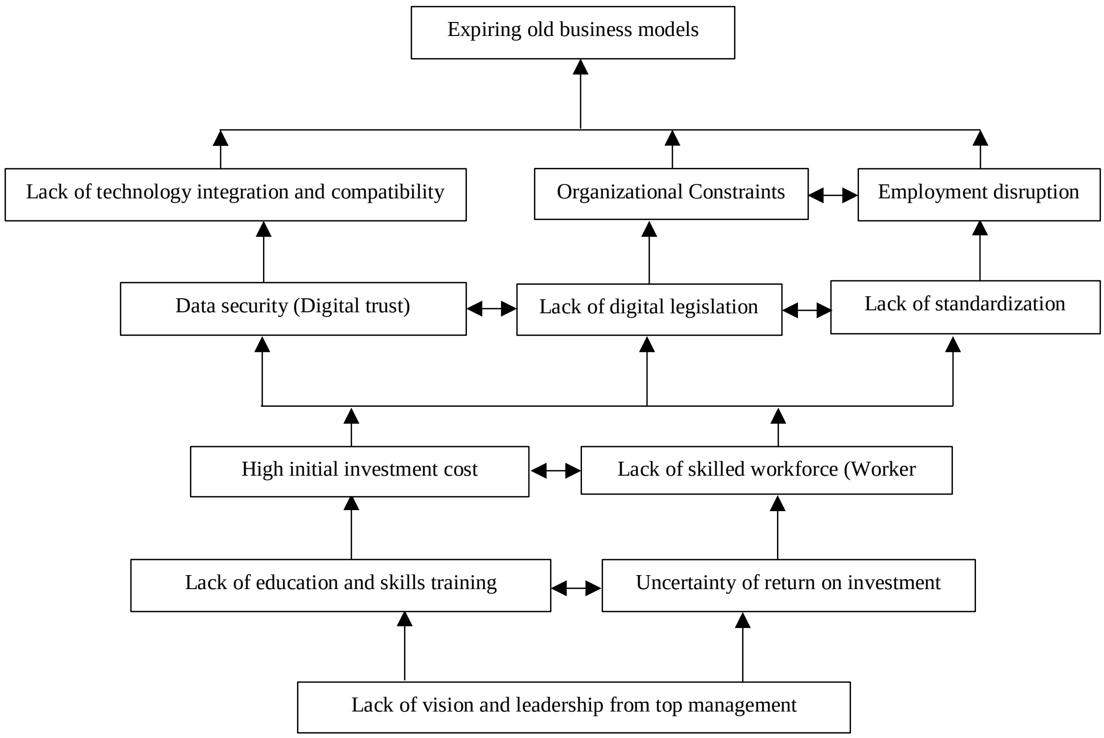

Figure 4. Final ISM model

positioned at the top of the model, which means it cannot influence/affect the challenges below its level but it is influenced/affected by them. In the same manner the Figure 4 shows the details of full ISM model for the remaining challenges.

2.1.7. Checking for Conceptual Inconsistency

Once again, the final ISM model is checked whether it has any conceptual inconsistency or not. This step is done by identifying and removing the intransitivity links in the ISM model.

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

Matrice d'Impacts croises-multipication applique´ an classment or in the short form MICMAC analysis is usually applied to analyze a group of elements or factors on the basis of their drive power and dependence power. MICMAC analysis uses the drive and dependence powers of the challenges to categorize them into the following groups or clusters:

Autonomous Cluster: is the first cluster and includes the challenges that are having weak drive power and weak dependence power. Therefore, these challenges are somehow separated from the system and have less effect on the system. *Dependent Cluster:* is the second cluster and is consist of challenges that are having weak drive power and strong dependence power. Therefore, they are dependent on other challenges and other challenges affect them. *Linkage Cluster:* is the third cluster and is consist of challenges that are having strong drive power and strong dependence power. These challenges connect the upper and lower level challenges with each other. These challenges are unstable in nature, because any action on them will have impacts on other challenges and a feedback effect on themselves. *Driver Cluster:* is the fourth cluster and is consist of the challenges that are having strong drive power but weak dependence power. These challenges are the main challenges and have the power to drive other challenges. Generally, these challenges are called as “key challenges”.

On the basis of drive power and dependence power the challenges are positioned into appropriate clusters. As it is depicted in Figure 5, none of the challenges fall into Autonomous cluster. The ‘organizational constraints (8) and expiring old business model (11)’ fall into the Dependent cluster. The “high investment on infrastructure (1), lack of skilled workforce (3), data security (4), lack of digital legislation (5), lack of standardization (6), uncertainty of return on investment (9), and employment disruption (10)” challenges fall into Linkage cluster that are having strong drive and dependence power. The “lack of education and skills training program (2) and lack of vision and leadership from top management (12)” challenges fall into Driving cluster. Therefore “lack of education and skills training program (2) and lack of vision and leadership from top management (12)” are the key challenges that

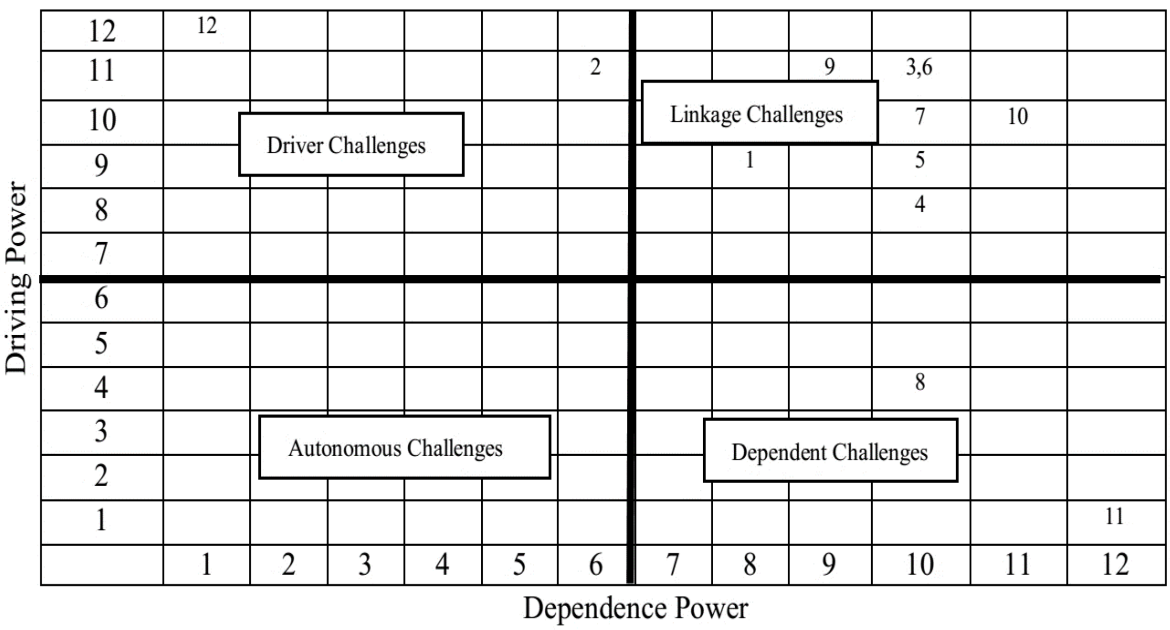

Figure 5. Driving power and dependence diagram of challenges for MICMAC analysis

have weak dependence power and strong drive power. Full details of MICMAC analysis for the challenges of Industry 4.0 implementation in manufacturing industries are shown in Figure 5.

2.2. Fuzzy-Analytic Hierarchy Process (F-AHP)

Analytic hierarchy process or shortly AHP is a multi-criteria decision-making technique that can be used to make decisions in situations where multiple objectives are involved. The AHP technique was developed by Saaty in 1980 [47] to solve complex decision-making problems. By applying AHP method any complex decision-making problem can be divided into different levels of sub-problems, where each level shows a set of criteria or attributes related to the specific sub-problem. AHP uses the process of pairwise comparison to formulate the hierarchy and prioritization among the criteria or attributes.

The traditional AHP method has shortcomings [48] because it uses a crisp scale of 1-9 for the pairwise comparison of the criteria and attributes [47]. The crisp scale of 1-9 cannot capture the uncertainty and vagueness of the human judgement, thus making the AHP method ranking imprecise. To overcome this problem, fuzzy sets theory is integrated with AHP to improve its preciseness. The fuzzy sets theory was proposed by Zadeh in 1965 [49] to incorporate the uncertainty and vagueness of human judgement in the calculations. Soon after, it got the attention of researchers to integrate the fuzzy sets theory with Multicriteria-Decision-Making (MCDM) techniques [50, 51, 52]. Hence, in the present study fuzzy-AHP is used to prioritize the Industry 4.0 implementation challenges in manufacturing industries. Three criteria are chosen to develop the fuzzy-AHP hierarchy (see figure 6) and are defined as follows:

I. Driving power of the challenges: It shows how a challenge influences other challenges and the priority will be given to the challenge which has the higher driving power.

II. Dependence power of the challenges: It shows how a challenge is being influenced by other challenges and the priority will be given to the challenge which has the higher dependence power.

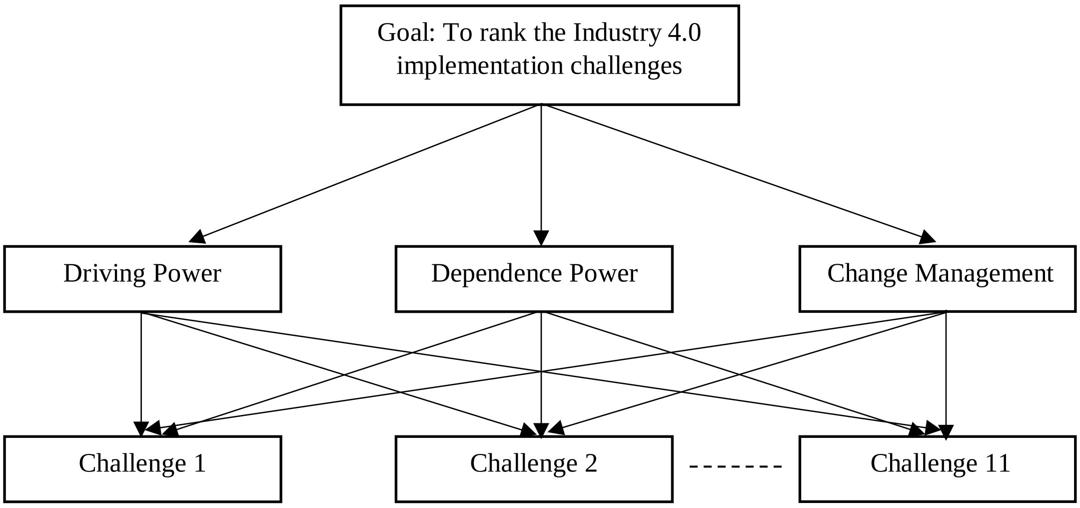

Figure 6. Fuzzy-AHP hierarchy structure

III. Change management: It shows the difficulties that the manufacturing industry or the organization experiences while dealing with the challenges in Industry 4.0 implementation. Therefore, priority will be given to the challenges that require less change management.

The driving power and dependence power are believed to be as beneficial criteria thus, a higher value or lower value of driving power and dependence power will lead to assignment of higher or lower priority during the pair-wise comparison respectively. Based on the above definition given for the change management, it is considered as non-beneficial criterion. In the pairwise comparison of the criteria and attributes, the fuzzy-AHP uses linguistic variables illustrated in the form of fuzzy trapezoidal numbers and fuzzy triangular numbers. Hence, in the present research, fuzzy triangular numbers are used to construct the comparison matrices.

Based on the Zadeh's (1965) [49] proposed fuzzy sets theory, a membership function that shows the membership value between zero and one, is used to represent a fuzzy set. Three values ($l \leq m \leq u$) can be used to represent a triangular fuzzy number, where *l* shows the lower bound, *m* shows the modal value and *u* shows the upper bound for fuzzy number $\tilde{A}$ as depicted in figure 7. The fuzzy number is defined by putting a tilde "~" symbol over it. The following equation shows the membership function calculation:

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-l}{m-l} & if \;\; l \leq x \leq m \\ \dfrac{u-x}{u-m} & if \;\; m \leq x \leq u \\ 0 & otherwise \end{cases} \quad (1)$$

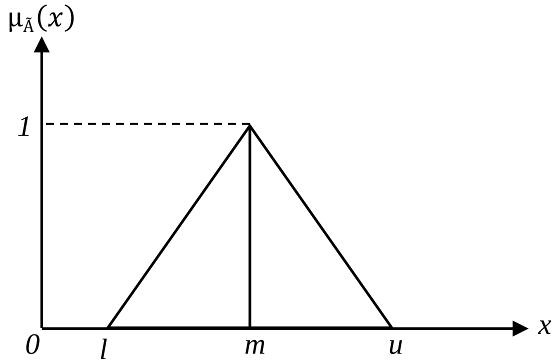

Figure 7. The membership function of Triangular fuzzy number

The process of fuzzy-AHP method is similar to the ISM methodology and a stepwise process must be followed to apply fuzzy-AHP, on this reason the steps involved in fuzzy-AHP are as follows: Step 1: In this step the scale of relative importance for the pairwise comparison matrix in form of fuzzy triangular number is defined and for the present study the linguistic variable, membership function and fuzzy number used is presented in Table 6.

Table 6. Conversion scale of fuzzy triangular number

Importance intensity	Fuzzy number	Linguistic variable	Membership function	Reciprocal membership function
1	~1	Equally important	(1,1,1)	(1, 1, 1)
3	~3	Weakly important	(1,3,5)	(1/5, 1/3, 1)
5	~5	Strongly important	(3,5,7)	(1/7, 1/5, 1/3)
7	~7	Very strongly important	(5,7,9)	(1/9, 1/7, 1/5)
9	~9	Extremely more important	(9, 9, 9)	(1/9, 1/9, 1/9)

Step 2: The experts' opinions and judgements are obtained to construct the fuzzy pairwise comparison matrix for the criteria and attributes. In the pairwise comparison matrix (*A*) shown below, d_{12} shows the decision maker's choice of 1st criterion over 2nd criterion through a triangular fuzzy number. Table 7 shows the fuzzy pairwise comparison matrix for the criteria.

$$A = \begin{bmatrix} d_{11} & d_{12} & .. & .. & d_{1n} \\ d_{21} & d_{22} & .. & .. & d_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ d_{n1} & d_{n2} & .. & .. & d_{nn} \end{bmatrix} \tag{2}$$

Table 7. Fuzzy pairwise comparison of criterion.

Criterion *i*	Driving power	Dependance power	Change management
Driving power	(1,1,1)	(5,7,9)	(1,3,5)
Dependance power	(1/9,1/7,1/5)	(1,1,1)	(1/7,1/5,1/3)
Change management	(1/5,1/3,1)	(3,5,7)	(1,1,1)

Step 3: Based on the equation (3) the geometric mean (r_i) of the fuzzy pairwise comparison matrix is calculated. Table 8 shows the calculated geometric mean of fuzzy comparison of the criteria.

$$\tilde{r}_i = \left(\prod_{j=1}^{n} d_{ij} \right)^{\frac{1}{n}} \tag{3}$$

Table 8. Geometric mean for the criteria.

Criterion *i*	Geometric mean r_i		
	l	*m*	*u*
Driving power	1.710	2.759	3.557
Dependance power	0.251	0.306	0.405
Change management	0.843	1.186	1.913
Total	2.805	4.250	5.875
Inverse	0.357	0.235	0.170
Ascending order	0.170	0.235	0.357

Step 4: Equations 4-6 are used to calculate the fuzzy weights (w_i), the de-fuzzified weights (M_i) and

$$w_i = r_i \times (r_1 + r_2 + \dots + r_n)^{-1} \tag{4}$$

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \tag{5}$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{6}$$

normalized weights (N_i) for the criteria. These weights are tabulated in Table 9.

Table 9. Fuzzy weights, de-fuzzified weights and normalized weights of the criteria.

Criterion *i*	w_i			M_i	N_i
	l	*m*	*u*		
Driving power	0.291	0.649	1.268	0.736	0.618
Dependance power	0.043	0.072	0.145	0.086	0.073
Change management	0.144	0.279	0.682	0.368	0.309

After calculating the weights for the criteria, the same procedure is followed to obtain the weights (*Wi*, *Mi* and *Ni*) for the alternatives with respect to each criterion. Tables 10-13 show the fuzzy-AHP application process for the alternatives and Table 14 shows the total weights of each challenge with respect to each criterion. Based on the maximum value of the total weight, the critical challenges affecting the implementation of Industry 4.0 in manufacturing industries are identified and ranked. Table 14 shows the final results of the fuzzy-AHP analysis.

Table 10. Fuzzy pairwise comparison of challenges with respect to criterion 1 (driving power).

Challenge	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(1,3,5)	(5,7,9)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(3,5,7)	(1/9,1/7,1/5)

C2	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(3,5,7)	(3,5,7)	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1/5,1/3,1)	(5,7,9)	(1/7,1/5,1/3)
C3	(1,3,5)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(1,1,1)	(3,5,7)	(3,5,7)	(1,1,1)	(1,3,5)	(5,7,9)	(1/7,1/5,1/3)
C4	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(1/7,1/5,1/3)	(3,5,7)	(5,7,9)	(1/9,1/7,1/5)
C5	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1/7,1/5,1/3)
C6	(1,3,5)	(1,1,1)	(1,1,1)	(3,5,7)	(1,3,5)	(1,1,1)	(1,3,5)	(3,5,7)	(1,1,1)	(1,3,5)	(1,3,5)	(1/9,1/7,1/5)
C7	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(9,9,9)	(5,7,9)	(1/9,1/7,1/5)
C8	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1,3,5)	(1/7,1/5,1/3)
C9	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)	(1,1,1)	(3,5,7)	(5,7,9)	(1/7,1/5,1/3)
C10	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)	(1/9,1/7,1/5)
C11	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1/9,1/7,1/5)
C12	(1/5,1/3,1)	(3,5,7)	(3,5,7)	(5,7,9)	(3,5,7)	(9,9,9)	(5,7,9)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(1,1,1)

Table 11. Fuzzy pairwise comparison of challenges with respect to criterion 2 (dependence power).

Challenge	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/9,1/9)	(1/5,1/3,1)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(3,5,7)
C2	(1,3,5)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1,3,5)
C3	(9,9,9)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1,3,5)
C4	(1/5,1/3,1)	(1,3,5)	(3,5,7)	(1,1,1)	(1,3,5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(3,5,7)
C5	(1,3,5)	(3,5,7)	(5,7,9)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)
C6	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(5,7,9)
C7	(5,7,9)	(3,5,7)	(1,1,1)	(1,3,5)	(5,7,9)	(1,3,5)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1/7,1/5,1/3)	(1,3,5)
C8	(1,3,5)	(3,5,7)	(3,5,7)	(1/5,1/3,1)	(1,3,5)	(3,5,7)	(1,3,5)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1,3,5)
C9	(3,5,7)	(1,3,5)	(1,3,5)	(3,5,7)	(9,9,9)	(1,1,1)	(3,5,7)	(3,5,7)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)
C10	(3,5,7)	(3,5,7)	(5,7,9)	(9,9,9)	(1,3,5)	(3,5,7)	(1/5,1/3,1)	(1,3,5)	(1,3,5)	(1,1,1)	(1,1,1)	(9,7,5)
C11	(5,7,9)	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)	(1,3,5)	(3,5,7)	(5,7,9)	(3,5,7)	(1,1,1)	(1,1,1)	(5,7,9)
C12	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1,1,1)

Table 12. Fuzzy pairwise comparison of challenges with respect to criterion 3 (change management).

Challenge	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(3,5,7)	(5,7,9)	(1,3,5)	(1,3,5)	(3,5,7)	(1/5,1/3,1)	(1,3,5)	(3,5,7)	(1/7,1/5,1/3)
C2	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(5,7,9)	(3,5,7)	(1,3,5)	(3,5,7)	(1,3,5)	(5,7,9)	(1/5,1/3,1)	(5,7,9)	(1/9,1/7,1/5)

C3	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1,3,5)	(1,3,5)	(5,7,9)	(3,5,7)	(3,5,7)	(1,3,5)	(5,7,9)	(1/7,1/5,1/3)
C4	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(3,5,7)	(1/9,1/9,1/9)
C5	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(3,5,7)	(1/5,1/3,1)	(3,5,7)	(1/7,1/5,1/3)
C6	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(3,5,7)	(1,1,1)	(3,5,7)	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)	(1/7,1/5,1/3)
C7	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(3,5,7)	(1,3,5)	(1/7,1/5,1/3)	(1,1,1)	(3,5,7)	(1,3,5)	(1,1,1)	(5,7,9)	(1/9,1/9,1/9)
C8	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)	(3,5,7)	(1,3,5)	(1/7,1/5,1/3)
C9	(1,3,5)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,3,5)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(5,7,9)	(5,7,9)	(1/7,1/5,1/3)
C10	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1,3,5)	(1,3,5)	(1/7,1/5,1/3)	(1,1,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1,1,1)	(3,5,7)	(1/9,1/7,1/5)
C11	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1,1,1)	(1/9,1/7,1/5)
C12	(3,5,7)	(5,7,9)	(3,5,7)	(9,9,9)	(3,5,7)	(3,5,7)	(9,9,9)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(1,1,1)

Table 13. Total weights for each challenge with respect to each criterion.

Criterion	Weights	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Driving power	0.62	0.072	0.09	0.109	0.041	0.036	0.095	0.065	0.041	0.108	0.035	0.014	0.294
Dependence power	0.073	0.022	0.034	0.029	0.064	0.036	0.081	0.097	0.085	0.111	0.170	0.243	0.027
Change management	0.309	0.113	0.118	0.139	0.027	0.038	0.087	0.052	0.039	0.053	0.042	0.012	0.279
Total	1	0.081	0.095	0.112	0.039	0.037	0.091	0.063	0.044	0.092	0.047	0.029	0.269

Table 14. Rank and prioritization of Industry 4.0 implementation challenges.

Challenge abbreviation	Challenge name	Total weight	Rank
C12	Lack of vision and leadership from top management	0.269	1
C3	Lack of skilled workforce	0.112	2
C2	Lack of education and skills training program	0.095	3
C9	Uncertainty of return on investment	0.092	4
C6	Lack of standardization	0.091	5
C1	High initial investment cost on infrastructure	0.081	6
C7	Lack of technology integration and compatibility	0.063	7
C10	Employment disruption	0.047	8
C8	Organizational constraints	0.044	9
C4	Data security	0.039	10
C5	Lack of digital legislation	0.037	11
C11	Expiring old business models	0.029	12

3. Results and Discussion

In the present study, based on an extent literature review the major challenges of implementing Industry 4.0 in manufacturing industries has been identified and highlighted. The ISM methodology was used to analyze the relationship, identify the interaction and establish the hierarchy among the challenges. ISM methodology works based on the experts' opinion and is an approach that uses a methodical, orderly and rational thinking, to solve the problems consisting large number of elements. As a result, six experts-three industrial professionals and three academic experts-were consulted to develop the ISM model showing the hierarchy among the identified challenges. The developed model shows the "lack of vision and leadership from top management (C12)" and "expiring old business models (11)" challenges positioned at basis and top of the model. The "lack of vision and leadership from top management (12)" challenge influences and affects other challenges as it is placed at the basis of the model and conversely, the "expiring old business models (11)" challenge is influenced and affected by other challenges. The remaining challenges are placed at the middle of the model indicating, these challenges are either influenced or influencing each other (see figure 4). Moreover, the MICMAC analysis was used to analyze the driving power and dependency of the challenges and categorize them into: driver challenges, autonomous challenges, dependent challenges and linkage challenges. Figure 5 gives the full details of the MICMAC analysis for the all 12 challenges and provides some important insights associated with relative importance and inter-dependence among the Industry 4.0 implementation challenges in manufacturing industries. The key challenges, which are identified by MICMAC analysis are "lack of education and skills training program (C2)" and "lack of vision and leadership from top management (C12)". The key challenges are the main cause in triggering other challenges. The challenges "organizational constraints (C8)" and "expiring old business model (C11)" are identified as the least affecting challenges as they fall into dependent cluster and are called as the dependent challenges.

Furthermore, the driving power and dependence power of the challenges derived from ISM analysis established two criteria for prioritizing the challenges. The change management required for implementing Industry 4.0 in manufacturing industries was considered as the third criterion. Fuzzy-AHP method was used to prioritize the challenges of implementing Industry 4.0 in manufacturing industries with respect to the criteria (driving power, dependence power and change management). Based on the final results obtained from the fuzzy-AHP technique, the "lack of vision and leadership from top management (12)" challenge is ranked as the top challenge and the "lack of education and skills training program (C2), lack of skilled workforce (C3), uncertainty of return on investment (C9) and lack of standardization (C6)" challenges as the major barriers in implementing Industry 4.0 in manufacturing industries. As shown in Table 14, "expiring old business models (11) and lack of digital legislation (C5)" are identified to be the least significant challenges in Industry 4.0 implementation.

6. Conclusion

The ISM analysis is used in the current study to evaluate the nature of challenges present in Industry 4.0 implementation in the manufacturing industries. The developed model showed that "lack of vision and leadership from top management (C12)" is the major challenge in implementing Industry 4.0 in manufacturing industries. This challenge influences the challenges "lack of education and skills training program (C2) and uncertainty of return on investment (C9)" toward the implementation of Industry 4.0. The "lack of education and skills training program (C2)" causes the "lack of skilled workforce (C3)" and "uncertainty of return on investment (C9)" creates ambiguines towards investments for the implementation of Industry 4.0 thus, affecting the challenge "high initial investment cost on infrastructure (C1)". Further, these challenges influence the challenges in upper level over them. In the upper most level of the model, challenge "expiring old business models (C11)" is indicated as the least affecting challenge. The developed ISM hierarchical model will help the industrial managers to understand the nature of challenges and their relationships so that management decisions can be taken accordingly to improve Industry 4.0 implementation in manufacturing industries.

The present research shows that the challenges, namely, "lack vision and leadership from top management (C12) and lack of education and skills training program (C2)" have high driving powers and this signifies the need for industrial managers to create skills training programs to educate their employees and motivate them to upgrade their skills, as a result it reduces the effect of the challenge "lack of skilled workforce (C3)" for the implementation of Industry 4.0. The ISM methodology besides its usefulness, it suffers from some limitations arising out of the selection of experts for judging the relationship between challenges and the expert bias who is rating the challenges, might affect the end result.

To overcome the vagueness, ambiguity and fuzziness in ISM technique, the fuzzy-AHP methodology is used to prioritize the challenges based on the output of ISM technique. The prioritization by fuzzy-AHP reveals the importance of having a clear vision and effective leadership for the top-level management for implementing Industry 4.0 in manufacturing industries. The top-ranked challenges show the need for skills and training programs that enable employees for work in an Industry 4.0 factory. Ultimately, the results of ISM and fuzzy-AHP reveal the significance of high initial investment cost on infrastructure, uncertainty of return on investments and lack of skilled workforce for the implementation of Industry 4.0 in manufacturing industries.

6.1. Limitations and Future Scope

In this research only the keyword "Industry 4.0" and "Fourth Industrial Revolution" was used to search for the papers to be included in the review, but synonymous of this concept such as, "IoT", "Internet of Things", "Digital manufacturing" etc., could be used as well. The exclusion of these keywords may have led to exclusion of important articles that can be used in future study. Conversely, the papers included in the review were not limited to a specific field of manufacturing industry but considered all the fields of manufacturing industry. Thus, future work may investigate separately and in a deeper way a specific field such as textile manufacturing, chemical manufacturing, electrical equipment and appliance manufacturing, and etc.

Another limitation which may have affected the result of this research is the establishment of contextual relation among the challenges in developing the ISM model, because it depends on experts' knowledge and familiarity with the Industry 4.0 and manufacturing industries' operations and processes. Thus, the expert bias who is rating the challenges, might affect the end result. Moreover, the analysis is done on the basis of the existing literature and in future new challenges may emerge or the existing challenges may not be as a challenge anymore. Finally, in further studies one can employ the Structural Equation Modelling (SEM) to statistically evaluate the developed model and can perform a comparative study of the identified challenges.

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