Analysing roadblocks of industry 4.0 adoption using graph theory and matrix approach

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Abstract: The manufacturing era is going through an evolutionary phase from Industry 3.0 to Industry 4.0 (I4.0). In 2011, Germany initiated I4.0 during the Hanover fair in collaboration with industrialists, academicians and researchers. The benefits of implementing I4.0 are attracting the curiosity of practitioners. In current academic literature, there is little discussion related to analysing potential roadblocks of I4.0 implementation using mathematical modelling. This paper has identified roadblocks through an extensive literature review and validation has been carried out by gathering experts' opinions. As per the findings, the identified roadblocks have been categorized into five sections: management roadblocks, operational roadblocks, human resource roadblocks, procedural and behavioural roadblocks. A case study of the automobile industry has been discussed. The data was collected from experts in the area of I4.0. A Graph Theory and Matrix Approach (GTMA) was applied to evaluate the relative intensity of the roadblocks, Comprehensive I4.0 Index (CII) and its range for each category of roadblock. Implications for industrialists, practitioners and academicians are provided.

Keywords: Industry 4.0 (I4.0) roadblocks, Graph Theory and Matrix Approach (GTMA), Comprehensive I4.0 Index (CII), operational excellence.

1. Introduction

Manufacturing industries have a significant impact on the development of every country. In the current digitalized era, industries are making strenuous efforts to survive in the competitive marketplace. Manufacturing industries have started to consider Industry 4.0 (I4.0) implementation, which was merely a buzzword in the last decade. I4.0 encompasses various technologies like Internet of things (IoT), Cloud computing, Cyber-Physical System (CPS), Cyber-Security, augmented reality, virtual reality and big data analytics [16]. Frank *et al.* [16] discussed the required components for successful implementation of I4.0 as smart supply chain (SC) or digital SC, smart manufacturing, smart products and smart working. Yin *et al.* [54] discussed I4.0 evolution through I2.0. Kamble *et al.* [26] and Rajput and Singh [44] described employee resistance and adaptability, high investment, reorganization of processes, smart skill requirements, deficiency of integrated approach towards knowledge management, unclear comprehension of I4.0 benefits and lack of standards, methodologies and techniques as the principal roadblocks of I4.0. These results were found to be in agreement with Kumar *et al.* [30] who analysed 15 challenges for adoption of I4.0.

Another significant factor in I4.0 implementation is human resources; this has always been a cherished asset of any organization [45]. Fareri *et al.* [15] described the human skills requirements of smart operators in I4.0 as consisting of three components: everyday execution skills, operational and functional skills. Employees have been cautious to embrace changes, fearing that I4.0 will replace the work done by humans and that all industrial operations in the manufacturing system will become automatic. Various researchers, Kaasinen *et al.* [25], Longo *et al.* [34], Rauch *et al.* [45], Romero *et al.* [48], have addressed these concerns, clarified any ambiguity and explained the anthropocentric views while using I4.0 technology. Kaasinen *et al.* [25] discussed solution measures in terms of empowerment and engagement for the smart operator. The authors further explained the differences between augmented, virtual, smarter, healthier, social, analytical or collaborative operator and a super strength operator. In a I4.0 working environment, human-automation symbiosis is mainly focused with key elements being a Human Cyber-Physical System (CPS) and adaptive automation [48]. The objective of human-CPS is to provide assistance to operator 4.0 with fundamental ergonomics considerations. This results in enhancing creativity, usability and innovation without having to negotiate on production goals [48]. Romero *et al.* [48] also discussed a Ceit Ergonomics Analysis Application (CERAA), a mobile application which was developed for the working location of operators and for risk assessment. With these perspectives in mind and after an extensive literature review, we feel that more academic research needs to be done to analyse roadblocks of I4.0 adoption using a Graph Theory and Matrix Approach; therefore, the objectives of the research are defined as:

- To identify the distinctive roadblocks for adoption of Industry 4.0 (I4.0)
- To develop a mathematical model and measure the intensity of each category of roadblock
- To evaluate comprehensive I4.0 Index (CII)

The structure of the remainder of the paper is as follows: theoretical background is discussed in section 2 followed by research methodology in section 3. An application towards quantifying each category of roadblock and its range is presented in section 4. The penultimate section contains results, discussion plus implications for industrialists, practitioners and academicians. The last section presents the conclusion, limitations and scope for future work.

2. Theoretical Background

This section explains the I4.0 concept and its core technologies, ergonomics requirements and research gaps.

2.1 Industry 4.0 Concept

Industry 4.0 (I4.0) deals with the amalgamation of machine tools with advanced manufacturing tools and technologies [12], [16]. I4.0 or smart manufacturing is the integration of flexible production lines in which machines/equipment are capable of selflearning capabilities by using machine learning algorithms [13], [38], [52]. IoT enables the machines/equipment to connect and share information over wireless networks through sensors and computing technologies [34]. An integrated manufacturing system based on IoT helps to gather large amounts of data from a variety of fields; this is called big data [16]. This raw data needs to be converted into useful information using cognitive computing systems. Sending data and information via wireless networks is susceptible to predatory attacks. Therefore, cyber-security is also a key concern to maintain veracity and confidentiality of data. Another significant pillar of I4.0 is augmented reality; this makes the operator's job easier by enabling operators to use digital information and superimpose that data with physical work conditions [37]. Longo *et al.* [34] explained the smart worker's role in the I4.O environment; it requires a person to be highly creative and have critical problem solving, reasoning and cognitive skills. Mital and Pennathur [40] analysed the relationship between humans and advanced technologies in manufacturing industries.

2.2 Ergonomics aspects in industrial revolutions

Despite so many automation technologies being available, human factors still play a crucial role in I4.0 implementation [5], [33], [34], [45], [48]. In the first industrial revolution, the requirement of physical ergonomics was greater as compared to cognitive ergonomics. Advancements throughout industrial expansion led to a decrease in physical ergonomics and subsequently an increase in the required level of cognitive ergonomics. Since I4.0 deals with complex operations, smart operators are required in the design of human-computer interfaces, supervision, maintenance and control of operations [34]. Engineer 4.0 or smart operators are required in I4.0 to deal with a complexity of operations, resulting in high cognitive loads [45], [48]. Recent published research papers on I4.0 with key findings are given in Table 1.

Table 1: Selected references of Industry 4.0

Reference	Key findings	Methods

Rajput and Singh [44]	High initial investment and energy consumption were discussed as an impediment to Industry 4.0 adoption. A need to revamp existing production facilities to smart manufacturing systems was felt necessary. A model was tested computationally with varying distance to achieve cleaner production and circular economy.	Mixed-Integer Linear Programming
Beier *et al.* [7]	Industry 4.0 was defined as a socio-technical system where technological, organizational and social aspects interact. Requirement to explore sustainability concerns in addition to performance and productivity.	Review Paper
Gunasekaran *et al.* [19]	Business Quality models in Industry 4.0 context were discussed. A study to align human factors and industrial revolution was discussed at macro and micro levels of engagement.	Theoretical framework
Leong *et al.* [32]	A case study of a thermal power plant was analysed to initiate lean and green perspectives. Lean Green Index (LGI) was computed; this can be utilized as a benchmark for industries trying to adopt Industry 4.0.	Machine Learning, ANP
Yadav *et al.* [53]	The concept of Sustainable Supply Chain Management (SSCM) and associated challenges towards its adoption were discussed and analysed. In total, 28 challenges towards adoption and 22 solution actions were discussed using an exhaustive literature review. The challenges in decreasing order of their intensity were evaluated as: Managerial > Supplier >process > socio-cultural.	Best Worst Method and ELECTRE
Chauhan *et al.* [10]	Recovering material using the 3R concept of circular economy was discussed. IoT enabled smart healthcare facility; waste disposal organizations and pollution control	DEMATEL

	board were found to have high intensity of causal effect.	
Esmaeilian *et al.* [14]	Research gaps and future research areas were framed. Further exploration of implementation of blockchain in Industry 4.0 was stated. Environmental sustainability aspects were mainly focused; social and economic aspects were found to require further investigation.	Case Study
Robert *et al.* [46]	Performance management model was developed by Schneider Electric to transform conventional manufacturing system into smart industry. Human factors and ergonomics were identified as core components along with technological system.	Case study

2.3 Research gaps

It has been found through an exhaustive literature review on available studies to date that various researchers e.g. Kamble *et al.* [26], Raj *et al.* [42] have explored the barriers to implementation of I4.0. But, from the review of relevant literature, no research study is available to devise a mathematical model of roadblocks of I4.0 implementation using GTMA. Based on these findings, the initial roadblocks of I4.0 are identified as shown in Table 2. Graph Theory and Matrix Approach (GTMA) methodology to find the relative intensity of roadblocks has been proposed. As a result, the roadblocks can be prioritized depending on their relative intensity. This will help managers to take the necessary actions and formulate strategies for successful I4.0 implementation.

Table 2: Key roadblocks identified through literature review

S. No	Roadblocks	Category	Sources
1	Fear of Technology Change		Horvath and Szabo [21], Ivanov

	(B_1^1)	Human Resource roadblock (B_1)	*et al.* [23], Jung *et al.* Hofmann and Rusch [20]
2	Enhanced Skill requirements (B_1^2)		Ivanov *et al.* [23], Kang *et al.* [28], Luthra and Mangla [35], Sanchez *et al.* [49]
3	Resistance to Change (B_1^3)		Khanzode *et al.* [29], Luthra and Mangla [35]
4	Lack of motivation (B_1^4)		Frank *et al.* [16], Lasi *et al.* [31], Luthra and Mangla [35]
5	Lack of passion for new technologies (B_1^5)		Frank *et al.* [16], Ivanov *et al.* [23], Jung *et al.* [24]
6	Regulatory compliance issues (B_2^1)	Behavioural roadblock (B_2)	Kang *et al.* [28], Longo *et al.* [34], Luthra and Mangla [35]
7	Lack of empowerment (B_2^2)		Horvath and Szabo [21], Ivanov *et al.* [23], Jung *et al.* [24], Luthra and Mangla [35]
8	Lack of recognition and reward system (B_2^3)		Bordel and Alcarria [9], Culot *et al.* [11], Luthra and Mangla [35]
9	Lack of Interpersonal skills (B_2^4)		Benitez *et al.* [8], Longo *et al.* [34]
10	Lack of clear understanding of I4.0 technologies (B_3^1)	Operational Roadblock (B_3)	Benitez *et al.* [8], Ivanov *et al.* [23], Kamble *et al.* [26], Luthra and Mangla [35]
11	Lack of Information and communication technologies (B_3^2)		Benitez *et al.* [8], Kamble *et al.* [26], Rafael *et al.* [43]
12	Security and Privacy Issues (B_3^3)		Benitez *et al.* [8], Horvath and Szabo [21], Jung *et al.* [24], Kang *et al.* [28]
13	Legal and contractual		Kamble *et al.* [26], Longo *et al.*

	uncertainty (B_3^4)		[34]
14	Organizational and Process change (B_3^5)		Horvath and Szabo [21], Jung *et al.* [24]
15	Lack of standards and reference architecture (B_4^1)	Procedural roadblock (B_4)	Longo *et al.* [34], Luthra and Mangla [35], Machado *et al.* [36]
16	Seamless integration and compatibility issues (B_4^2)		Frank *et al.* [16], Kamble *et al.* [26], Romeo *et al.* [47]
17	Lack of Research and development activities (B_4^3)		Asif [3], Frank *et al.* [16], Longo *et al.* [34]
18	Lack of knowledge management system (B_4^4)		Frank *et al.* [16], Ivanov *et al.* [23], Kang *et al.* [28], Li *et al.* [33]
19	Lack of continuous improvement culture (B_4^5)		Hwang *et al.* [22], Kang *et al.* [28], Longo *et al.* [34]
20	Lack of top management commitment (B_5^1)	Management roadblock (B_5)	Horvath and Szabo [21], Jung *et al.* [24], Longo *et al.* [34], Luthra and Mangla [35]
21	Lack of funds (B_5^2)		Frank *et al.* [16], Ghobakhloo [17], Horvath and Szabo [21]
22	Lack of understanding of the strategic importance of Industry 4.0 (B_5^3)		Frank *et al.* [16], Ivanov *et al.* [23], Jung *et al.* [24], Khanzode *et al.* [29]
23	Lack of digital business models (B_5^4)		Frank *et al.* [16], Luthra and Mangla [35], Machado *et al.* [36]
24	Lack of training and educational programs (B_5^5)		Frank *et al.* [16], Kang *et al.* [28], Longo *et al.* [34]

3. Research Methodology

The flow chart of research methodology is depicted in Fig.1. It is divided into three stages. First, to identify roadblocks of I4.0, an extensive literature review was conducted. The research database exploration was carried out using various prominent search engines such as Web of Science, Scopus, Science Direct and IEEE. These research databases were searched using a number of keywords - I4.0 roadblocks, smart manufacturing roadblocks, human factors and design in I4.0, ergonomics in I4.0, challenges of I4.0, drivers and enablers of I4.0, cyber-physical system etc. Abstracts and keywords were thoroughly studied, analysed and used as a basis for final inclusion in carrying out further research. Subsequently, inclusion and exclusion criteria were defined. The exclusion criteria were research articles written in languages other than English, magazine reviews, blogs etc. Background work on categorization of roadblocks was done through consultation with recognised experts. Experts were asked to validate the roadblocks already identified. Based on similar characteristics of the identified roadblocks, they were divided into five categories: operational, behavioural, human resource, management and procedural. A Graph Theory and Matrix Approach (GTMA) methodology was proposed; this was applied to quantify each category of roadblock and evaluate a comprehensive I4.0 Index (CII).

3.1 Some Applications of GTMA

Graph Theory and Matrix Approach (GTMA) has been applied in a variety of applications by various researchers all around the globe [56]. The various steps of the GTMA process are depicted in Figure 2. Mishra *et al.* [39] used GTMA for analysing a servitisation model in Indian automobile industries. The factors affecting servitisation were found to be physical resources, manpower, capital invested, government rules and regulations, service methodology and customer perspectives. Customer Service Quality Index for three organizations were evaluated and compared. Singh and Singru [50] analysed lean initiatives in complex manufacturing situations. Muduli *et al.* [41] evaluated barriers of green supply chain management. Attri *et al.* [4] computed total productive maintenance (TPM) barriers; The intensity of each sub-category barrier (IoB) was calculated and managerial implications were suggested to tackle these barriers. Aravind Raj *et al.* [2] have developed a mathematical model to estimate agile enablers. Management responsibility was found to be the key enabler affecting agility in a manufacturing organization. Agrawal *et al.* [1] have applied a graph theory approach to calculate attributes and sub-attributes of reverse logistics. The outsourcing index was estimated which helps managers greatly in outsourcing decisions.

Fig. 1: Research methodology process

4. An Application

In this section, an industrial case study has been considered. The industrial background, survey response, digraph construction, permanent function value computation and its range have been explained in the following sub-sections.

4.1 Industrial Background

India is ranked fourth globally in the automobile industry [27]. The manufacturing sector contributes to almost 50% of the GDP of the country [27]. This prominent sector has been forced to adopt green and sustainable manufacturing practices to achieve and maintain a competitive advantage [6-7,10]. Exports in the automobile sector have risen recently by approx. 17%, amounting to $15.16 trillion during the year 2018-19 [27]. The company ABC (located in the National Capital Region of India) was considered for analysis of I4.0 roadblocks. The company has pioneered work in supplying a transmission system to the original equipment manufacturers (OEMs) using state-of-the-art machinery. It has a dedicated flexible manufacturing system facility to cope with a differing product mix as per changing demand patterns. The company aims to provide high quality customized products to customers at competitive prices. It manufactures gears of various types and sizes - ring gears, pinions, transmission gears, spline gears, helical gears and shafts, differential gears, bevel gears etc. The turnover is $35 billion and it has 400 employees. An example from the automobile ancillary industry is discussed in this research. The current situation of the industry towards the adoption of I4.0 is analysed and compared with extreme situations (best and worst).

4.2 Survey Response and Data Collection

Experts from manufacturing industries were involved in collecting responses. In total, 15 experts were consulted to collect data. All of the experts were in high level positions (Head - Innovation and New Technology Development, Head - PPC, Head - R&D, Production Manager etc) and were well qualified. The threshold for qualification was set as graduate education and extensive exposure to industrial operations. All experts had more than 15 years of experience working in the sector; average length of experience was 17.2 years. The roadblocks identified were confirmed with expert opinion. Inheritance values on (1-9) scale and inter-dependencies values on (1-5) scale were collected, as shown in Table 3.

Table 3: Inheritance and Inter-dependency measure

Inheritance	Assigned	Inter-	Assigned

Measure	Value	dependency Measure	Value
Exceptionally low	1	Very Strong	5
Very low	2	Strong	4
Low	3	Medium	3
Below Average	4	Weak	2
Average	5	Very Weak	1
Above Average	6		
High	7		
Very High	8		
Exceptionally High	9		

Fig. 2: Mathematical Model of roadblocks of I4.0

Fig. 3: Digraph for Human Resource roadblock

Fig. 4: Digraph for behavioural roadblock

Fig. 5: Digraph for Operational roadblock

Fig. 6: Digraph for Procedural roadblock

Fig. 7 Digraph for Management roadblock

4.3 **Construction of Mathematical Model of I4.0 roadblocks**

The mathematical model of I4.0 roadblocks is depicted in Fig.2. The digraph is developed using nodes and edges. The term B_i represents roadblock inheritance whereas b_{ij} indicates degree of dependence of j^{th} on i^{th} roadblock (Attri et al.) [4].

b_{ij} = 1, if roadblock i is affecting roadblock j

= 0 otherwise

For instance, as shown in Fig.2, as Human Resource roadblock (B_1), Behavioural roadblock (B_2), Operational roadblock (B_3) and Procedural roadblock (B_4) are each dependent on Management roadblock (B_5), a direct arrow is drawn from B_5 to B_1, B_2, B_3 and B_4. The same procedure is repeated to construct a digraph for each category of roadblock as shown in Figure 3 to Figure 7.

4.4 Computation of Permanent function value

The variable permanent matrix (VPM) is given by Equation I which contains all five roadblocks i.e., operational, behavioural, human resource, management and procedural.

The method of calculation of the permanent value function is the same as that for calculation of the determinant. The only difference is negative signs are replaced with positive signs while calculating the permanent function value as this causes loss of information. The permanent of each roadblock is given as a mathematical expression in symbolic form. It is a measure to calculate the intensity of roadblocks in a particular organization.

per $(_{IR})$ =

Per (B_1) = Per(B_2) = Per (B_3) =

Per (B_4) = Per (B_5) =

4.5 **Computations Involved**

MATLAB is used for computation of permanent values of the I4.0 roadblocks. Per (B_1) = 111240, Per (B_2) = 5418, Per (B_3) = 127152, Per (B_4) = 13608, Per (B_5) = 137800. Depending upon the inter-dependencies among different roadblocks, the non-diagonal elements of the matrix are assigned scores according to values given by the experts (scale 1-5). The diagonal values are the permanent values of individual roadblocks as calculated using Equation 3 to Equation 7. Using Equation 1, VPM-IR is given by

(8)

The above matrix gives CII, i.e., comprehensive I4.0 Index. This index demonstrates the ability of the organization to adopt I4.0 and inter-dependencies among roadblocks involved. Comprehensive I4.0 Index = 1.4 x 10^{23} and corresponding logarithmic value Log_{10} (1.4 x 10^{23}) = 23.15

4.6 Range of I4.0 Roadblocks and Comprehensive I4.0 Index (CII)

Maximum value of CII is obtained when the diagonal elements have maximum value 9; the permanent function value is calculated in the same way. In that case, Per (B_1^{**}) = 147369, Per (B_2^{**}) = 11439, Per (B_3^{**}) = 190383, Per (B_4^{**}) = 92196, Per (B_5^{**}) = 167286. The comprehensive I4.0 Index (CII) in this case is 5 x 10^{24}. The corresponding logarithmic value in the best case is Log_{10} (5 x 10^{24}) = 24.70.

Similarly, for minimum value, the diagonal elements have minimum value 1; the permanent function value is calculated in the same manner. In this case, Per (B_1^{*}) = 2873, Per (B_2^{*}) = 431, Per (B_3^{*}) = 11575, Per (B_4^{*}) =1020, Per (B_5^{*}) =10398. Correspondingly, the comprehensive I4.0 Index is 1.5 x10^{17} and its logarithmic value is 17.18. Table 4 shows the compiled list containing permanent values of each roadblock.

Table 4: Permanent function value of current situation, best possible and worst possible situation

Roadblock	**Current Situation**	**Log_{10} Current Value**	**Max. Value**	**Log_{10} (Max Value)**	**Min. Value**	**Log_{10} (Min Value)**
Per (B_1)	111240	5.046	147369	5.168	2873	3.458
Per (B_2)	5418	3.733	11439	4.058	431	2.634
Per (B_3)	127152	5.104	190383	5.279	11575	4.063
Per (B_4)	13608	4.133	92196	4.964	1020	3.008
Per (B_5)	137800	5.139	167286	5.223	10398	4.017
CII	1.4×10^{23}	23.15	5×10^{24}	24.70	1.5×10^{17}	17.18

Fig. 8: RADAR diagram for the intensity of roadblocks

5 Discussion and Implications

The roadblocks have been categorized into five groups i.e. operational, behavioural, human resource, strategic management and procedural roadblocks. A case study of an automobile ancillary based company was conducted to assess the readiness of the organization towards I4.0 implementation. Subsequently, the comprehensive I4.0 Index (CII) and range of each category of roadblock have been calculated. The permanent values of each roadblock are converted into log scale for easy interpretation of results; these are shown in Table 4 and Figure 8. Thus, using Graph Theory and Matrix Approach (GTMA), self-analysis and comparison among industries can be carried out. The overall intensity of roadblocks taken together is shown by a single numerical value, i.e., comprehensive I4.0 Index (CII) = 1.4×10^{23}, its corresponding value on Log_{10} scale is 23.15. The maximum and minimum values are 24.70 and 17.18. Since, the CII value of 23.15 is very close to maximum value (24.70), it indicates an overall strong intensity of roadblocks.

The first high intensity roadblock is found to be Management roadblock (B_5). Its permanent function value is 5.139 and maximum value is 5.223. It includes lack of top management commitment (B_5^1), lack of funds (B_5^2), lack of understanding of the strategic importance of I4.0 (B_5^3), lack of digital business models (B_5^4) and lack of training and educational programs (B_5^5). The results found are in accordance with a study carried out by Raj *et al.* [42] which suggests that lack of top management commitment, lack of digital strategies and reduced amounts of available resources are the most significant roadblocks. Those in higher management must understand the strategic competitive advantages of I4.0 implementation. Lack of funds is also a major obstacle in the implementation of I4.0 [33]. Although the return on investment (ROI) is worthwhile, high initial capital is required to purchase the necessary machinery and equipment. Digital business models can help an organization to connect all over the globe [42]. This helps industries to deal with the pros and cons of every aspect of business and to identify fickle customer demand patterns in real-time. Also, training and educational programs needs to be organized on a periodical basis in order to develop the required skill-sets among employees.

The second significant roadblock is the operational roadblock (B_3); this consists of lack of clear understanding of I4.0 technologies (B_3^1), lack of information and communication technologies (ICT) (B_3^2), security and privacy issues (B_3^3), legal and contractual uncertainty (B_3^4) and organizational and process change (B_3^5). In most cases, at their manufacturing sites, companies do not have sufficient information and communication technology (ICT) facilities, the backbone of IoT enabled manufacturing systems [42]. Also, organisations are wary of data security and privacy issues, creating a resistance to adoption of a I4.0 system. Standardized cyber-security norms need to be formulated to ensure the security and privacy of data. Making amendments in an existing production system in compliance with I4.0 standards is another big challenge for those organisations planning implementation of I4.0.

The permanent function value of human resource roadblock (B_1) is the third-highest. Its value of 5.104 is very close to the maximum possible value, 5.279; this shows the strong resistance of human personnel towards the implementation of I4.0 technology. The various roadblocks under the human resource category are fear of technology change (B_1^1), enhanced skill requirements (B_1^2), resistance to change (B_1^3), lack of motivation (B_1^4) and lack of passion towards new technologies (B_1^5). In business, it is a widespread notion that I4.0 will replace human beings, thus creating unemployment. Yet a study carried out by Longo *et al.* [34], Tortorella *et al.* [51] clarified this ambiguity, stating that highly skilled smart operators will be required. Since the concept of I4.0 is relatively new, there is a scarcity of people with expertise in I4.0 associated technologies. In general, employees are reluctant to face new challenges and are content to stick to their normal busy schedules. Since the market is highly dynamic, employees are required to update themselves as per the latest market trends and technologies.

The next significant roadblock is a procedural roadblock (B_4). As the name signifies, this roadblock represents the procedure-related aspects of a manufacturing plant. It consists of the following sub-categories of roadblocks: lack of standards and reference architecture (B_4^1), seamless integration and compatibility issues (B_4^2), lack of research and development activities (B_4^3), lack of knowledge management system (B_4^4) and lack of continuous improvement culture (B_4^5). Use of standard methods, tools and equipment helps to achieve high-quality products with the least number of defectives. Research and development teams are required to work arduously to retrofit existing equipment and make it compatible as per I4.0 specification. Kaizen (continuous improvement) helps the organization to achieve operational excellence.

The last roadblock is behavioural roadblock (B_2); it includes regulatory compliance issues (B_2^1), lack of empowerment (B_2^2), lack of recognition and reward system (B_2^3) and lack of interpersonal skills (B_2^4). Companies who are considering implementing new systems are required to adhere to stipulated compliances and regulatory standards. Operators need to be empowered so that quick decisions can be taken for resolving bottlenecks arising at manufacturing sites. Recognition and reward systems in a company helps in motivating employees and keeping them focused on their work. It also facilitates the staff to work more diligently and effectively. Since I4.0 involves complexities of operations, strong interpersonal skills and efficient teamworking is essential. Understanding all these roadblocks and taking precautionary steps to address them, will help companies to overcome these roadblocks and implement Industry 4.0 with relative ease.

5.1 Implications for Managers and Academicians

The results of this research have produced implications for industrialists, practitioners and academicians. The key contribution is to encourage C-suite executives towards 14.0 adoption by strategically overcoming the roadblocks encountered. The unique contribution of the research is the production of a mathematical model. Comprehensive understanding of key roadblocks and overcoming it will lead to successful implementation of I4.0. Also, relative ranking of roadblocks will help managers to put their efforts in the right direction and formulate appropriate strategies accordingly. Self-assessment and self-realization of any loopholes can be better visualized by calculating the permanent function value of each category of roadblock. Necessary measures can be taken well in advance to overcome the roadblocks and can be used as a roadmap for I4.0 implementation. Thus, results will be extremely useful for those industrialists and practitioners willing to transform their manufacturing businesses from conventional to smart industry. Ultimately, adoption of I4.0 will result in increased quality of the product, improved customer satisfaction, optimum utilization of resources, better profitability and better sales. Implementing I4.0 will also result in reducing wastage, achieving sustainability and introducing a circular economy into the production system [18].

The results will also be equally valuable for academicians and educational institutions. Looking at the growing trends and developments in technology, I4.0 seeds must be sown earlier through education at school and at university level [55]. Courses focused on I4.0 technologies and associated laboratory practices need to be the part of the curriculum. In addition, if possible, governments may plan and implement educational policies to train faculty members in industrial innovation. This will help in disseminating practical knowledge and will enable sharing experience of updated technologies with students. As a result, budding engineers will become highly skilled, employable and self-dependent from an early age.

6 Conclusion, Limitations and Scope for Future Work

In a nutshell, the paper gives a comprehensive strategy of dealing with potential roadblocks using GTMA. Relative ranking of roadblocks in I4.0 adoption have been evaluated. The roadblocks in decreasing order of priority are listed as Management Roadblock, Operational Roadblock, Human Resource Roadblock, Procedural Roadblock and Behavioural Roadblock. Managers, industrialists, practitioners and policymakers can use this methodology as a benchmark; they will be able to compute and compare the relative intensity of roadblocks and produce a comprehensive I4.0 Index (CII) for their organisations. A preliminary analysis of the adoption of I4.0 can be conceptualized.

The study has some limitations. I4.0 is a vast and emerging domain of research. As such, listing and analysing all potential roadblocks simultaneously may be tedious and subject to errors. Furthermore, the GTMA methodology uses experts' inputs to enable all computations; any negligence in recording and evaluating responses may lead to inaccurate results. It is imperative to carry out data collection and evaluation carefully.

The roadblocks of I4.0 can be analysed using other decision-making techniques. A total interpretive structural modelling (TISM) technique can be used to identify interactions and structural relationships among roadblocks. In the current context, a case study of an automobile ancillary company in India is discussed and analysed. Multiple case studies can be conducted across the globe and results can be compared. Also, the present case study is focused on an automobile ancillary industry. Other sectors, such as power or electronics, can be considered to evaluate more results. In addition, the roles and skill-sets of smart operators required to work in a I4.0 environment need to be further explored.

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