Asia Pacific Management Review xxx (xxxx) xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Asia Pacific Management Review

journal homepage: www.elsevier.com/locate/apmrv

Identification and severity assessment of challenges in the adoption of industry 4.0 in Indian construction industry

Arpit Singh [a], Vimal Kumar [b, *], Pratima Verma [c], Jayakrishna Kandasamy [d]

[a] *Department of Information Systems and Analytics, O. P. Jindal Global University, Sonipat, 131029, India*
[b] *Department of Information Management, Chaoyang University of Technology, Taichung, 41349, Taiwan*
[c] *Department of Strategic Management, Indian Institute of Management, Kozhikode, 673570, India*
[d] *School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, 632014, India*

A R T I C L E I N F O

Article history:
Received 14 July 2022
Received in revised form
18 September 2022
Accepted 24 October 2022
Available online xxx

Keywords:
Industry 4.0
Severity assessment
Ranking
Internet of things
Construction industry
Dominance-based rough set analysis

A B S T R A C T

The current exploratory study identifies the major challenges in the adoption of Industry 4.0 framework in the Indian construction industry and subsequently ranks the challenges on the basis of the severity. Based on the extant literature review and personal interaction with construction management, information technology (IT) professionals, and academicians, twenty-five challenges were identified. After validating the challenges, they were ranked from most severe to least severe using the multi-criteria decision-making (MCDM) method based on rough set theory that leans on the indiscernibility relation between the objects. The study indicates that huge initial investments and costs incurred to mobilize the internet of things (IoT) enabled framework in the construction firms are the major obstacles to the adoption of the Industry 4.0 methods. The recruitment of experts to train the employees and workers is seen as another big hurdle in the aforementioned objective. It is a challenge to educate and train them on sophisticated technology that requires a basic understanding of computer fundamentals and IT-related concepts that is found lacking in the workers employed at the lower levels. Proper maintenance of sensitive tools and equipment such as IoT devices is a challenging task due to the nature of the activities taking place at construction sites. The multi-criteria method of ranking based on Dominance-based Rough Set Analysis (DRSA) has never been attempted to rank the challenges and assign a severity score. The study adds novelty to the existing literature in the domain of multi-criteria ranking by including a tool that is new to this area of research.

1. Introduction

In today's highly competitive market, every organization strives to have an edge over its competitors to be established and successful (Dobni et al., 2022; Sulistyo & Siyamtinah, 2016). The most sought-after method to gain a strong foothold in the business environment is to introduce smart technology in the production process that improves productivity and enhances efficiency (Moradi et al., 2021). The inevitable risks associated with the production process can be mitigated to a large extent using smart technology (Lin & Cheung, 2020). This, not only amounts to improving the returns but also serves to patrol the environmental risks and provide better products both qualitatively and quantitatively (Kim et al., 2017; Kolberg & Zühlke, 2015). In the wake of the urgent need to integrate automation and smart technology in the production process, Industry 4.0 has shown tremendous potential in the creation of a smart infrastructure that aids in establishing a framework that addresses the three P's i.e. people, profit, and the planet, of the Triple bottom line (TBL) approach in industries (Chen, 2022). Thus, the adoption of Industry 4.0 in organizations can lead to economic, social and sustainable manufacturing systems (Arpaci, 2019). Originated as a part of a high-tech project in Germany with the main focus on computerization in manufacturing, Industry 4.0 is a strategically thought-out step that is taken towards creating

* Corresponding author. Department of Information Management, Chaoyang University of Technology, Taichung, Taiwan.

E-mail addresses: asingh6@jgu.edu.in (A. Singh), vimaljss91@gmail.com, vimalkr@gm.cyut.edu.tw (V. Kumar), way2pratima@gmail.com, pratima@iimk.ac.in (P. Verma), mail2jaikrish@gmail.com, jayakrishna.k@vit.ac.in (J. Kandasamy).

Peer review under responsibility of College of Management, National Cheng Kung University.

https://doi.org/10.1016/j.apmrv.2022.10.007

smart factories where different technologies like robotics, cloud computing, artificial intelligence, internet of things (IoT), communications technology, big data analytics, virtual reality are integrated to promote interaction between humans and equipment thereby making the system intelligent with the use of human inputs (Banmairuroy et al., 2022; Chen et al., 2018; Hofmann & Rüsch, 2017; Hsieh & Wu, 2019). Industry 4.0 is a term broadly associated with automation and data exchange in manufacturing technologies. It consists of cyber-physical systems (CPS) at the core of its principles. Loosely referred to as the fourth industrial revolution, Industry 4.0 essentially represents a combination of IoT, internet of systems (IoS) and CPS (Hasan et al., 2019; Longo et al., 2017; Lu, 2017; Rojko, 2017). As stated earlier, the fundamental advantage that Industry 4.0 promises are to invent the idea of smart factories. A smart factory implies a scenario where the machines are connected to the web which is further connected to a system that can observe the entire production chain and make decisions on its own (Forbes, 2019; Yoon et al., 2020). The phase of the fourth revolution or Industry 4.0 marks the point in time where a multitude of emerging technologies are witnessed from all domains including physical, digital and biological that are closely connected. It is this inter-relationship between the technologies that impact every discipline, economy, and industry. Industry 4.0 holds the potential of checking and undoing the disasters that the earlier three revolutions inflicted on the environment by regenerating natural resources through better asset management.

The construction sector in India continues to grow due to increased demand for infrastructure and real estate. It is a major indicator of the development as it generates and promotes investment opportunities in other related sectors. The current study will enable the senior management in the small-scale Indian construction industry to discover the reasons behind the inability to adopt Industry 4.0 enabled framework in their organizations particularly, small-scaled firms with limited resources. It is expected that India is going to be the third-largest construction market globally with a GDP contribution of about 15% by 2030. It is also speculated that the construction industry will employ more than 75 million people by 2022 (Make in India, 2019). The Government of India (GoI) has placed high stakes in the construction industry as it realizes that the ever-increasing demands from the urban population are not adequately met with the given levels of urban infrastructure. There is a need for the regeneration of urban areas in the existing cities and the creation of new smart cities that can cater to the demands of the population and migration from rural to urban areas. The reports published by the GoI state that Gross Value Added (GVA) registered a growth of 4.3% as compared to 1.3% in the last year. Capitalizing on the information technology (IT) expertise and large IT workforce, India has already begun venturing into the fourth industrial revolution. Under the Government of India's “smart cities mission”, it is hoped that the project shall build 100 smart cities across India (Make in India, 2019). Indian Institute of Science (IISc) has started building the first smart city in the city of India, Bengaluru with the seed funding received from Boeing Company (Industry 4.0, 2019). The Secretary of the Department of Industrial Policy and Promotion (DIPP) observes the tremendous potential and doors of opportunities Industry 4.0 can open for India. While automation has transformed the manufacturing scenario completely, the construction sector is yet to benefit from automation and smart machines. There is a big scope and opportunity to involve smart concepts in the construction process and drastically improve the efficiency and quality of the outcome or product. The use of three-dimensional (3D) printing, robotics, and artificial intelligence (AI) has already been applied in various facets of construction activities to improve the overall standard of production and save time and ensure the safety of the workforce. Some of the notable advancements in the integration of automation in the construction sector are Eidgenössische Technische Hochschule (ETH) Zurich's In-situ fabricator that will be creating non-rectilinear walls by constructing a double layer of metal bars. The fabricator is a robotic arm using mesh mold technology. Construction robotics *self-automated mason* has the capability of putting down 6000 bricks per day. An instance of the effectiveness of 3D printing in building walls can be had from the gantry printer's building Copenhagen's building on demand (BOD) that will be laying down concrete 50–70 mm thick at 2.5 m per minute. The Media Lab of the Massachusetts Institute of Technology (MIT) has used an industrial robotic arm to create the *Digital Construction Platform* (DCP) that has the ability to move anywhere at the construction site and construct as it goes (ASME, 2019). The manufacturers can increase the efficiency of the production by optimizing the operations by focusing and streamlining the attention to the problem areas without having to waste energy, time, and resources. Micro, small and medium enterprises (MSMEs) are touted to be the biggest gainers of Industry 4.0 by transitioning to the new technology (Financial Express, 2019).

Industry 4.0 shows great potential for revamping the Indian Construction Industry by facilitating enhanced productivity through optimization and automation, making real-time data available for use for real-time supply chains in the real-time economy, greater business continuity through advanced maintenance and continuous monitoring, and providing higher quality products as a result of real-time monitoring, IoT and IoS enabled processes and quality control. Industry 4.0 holds the potential to revamp the operations in the construction sector by adopting the principles of a “smart city”. The smart city is an idea where the functions are optimized to drive economic growth while improving the quality of life using smart technology and data analysis (Yigitcanlar et al., 2021). The adoption and application of mobile computing through data management networks such as IoT, big data, and cloud computing technologies form the backbone of smart cities (Kirimtat et al., 2020). Tapping on the concept of smart technology is often considered the best solution to the problems related to transportation, waste management, and environmental protection (Laufs et al., 2020). The adoption of Industry 4.0 is still under apprehension. Most of which is attributed to the high investment costs needed to establish the framework and necessary skills to have effective and smooth functioning.

The paper is divided into six sections. Section 2 reflects on the past literature on the topic of the IoT and several other aspects of a smart factory. Section 3 illustrates the methodology adopted for carrying out the analysis. Section 4 presents the results and discussion of the study with a sub-section on additional analysis to assess the sensitivity of the results. Section 5 discusses the implications including theoretical and managerial implications of the study followed by the conclusions, limitations and future scope in Section 6.

2. Literature review

Industry 4.0 is the current automation trend and data exchange platform in manufacturing technologies. It includes cyber-physical systems (CPS), the IoT, and cloud computing that collectively creates the smart factory. The key components comprising Industry 4.0 are reviewed briefly in the subsequent sub-sections.

2.1. Cyber-physical system

Cyber-physical system or CPS forms an integral part of the Industry 4.0 framework. CPS is fundamentally a combination of cyber systems and physical systems interacting with each other on a real-time basis and hence the name Cyber-Physical System. The conceptual framework of CPS is envisioned in Fig. 1.

Physical systems have computerized systems in-built in them that assist in various functionalities automatically. For instance, consider a car as a physical system and ADS as a computerized unit that controls the brakes of the car automatically. Now, the ADS interacts with the physical world through the sensing devices such as sensors. Sensors are equipment that is sensitive to light, radiation, and other forms of energy that when coming in contact with send out signals to a measuring or calibrating instrument. The data or the information gathered by the sensors and the brake system are fed to the cloud or a communication network such as the Internet. The data is processed in this segment through a decentralized information processing unit or a human-computer interface. The processed data yields results which are transmitted to the actuators and corresponding appropriate action is executed such as the application of brakes, etc. The combination of computerized systems, sensors, and actuators constitute embedded systems. The concept of CPS has been extensively studied across all disciplines along the lines of the applications, integration with existing technologies and challenges faced in the implementation.

In order to transform the manufacturing industry to the next generation of technology, that is Industry 4.0, a clear definition of CPS is needed. A systematic deployment of CPS within which the information from all the departments of a production process can be monitored and synchronized between the physical world and cyberspace prompted the authors to create a unified five-level architecture that serves as a guideline for the implementation of CPS (Lee et al., 2015).

CPS are systems of networks of collaborating computational technologies that are connected intensively with the physical world and operate to improve the efficiency of the process by providing real-time data and using data processing services available on the internet to yield accurate results. The author establishes the significance of adopting CPS in manufacturing to improve production resulting in the framework referred to as cyber-physical production systems (CPPS) (Monostori et al., 2016). The integration of CPS with the construction process was studied in light of the bi-directional coordination between the construction and the virtual world. It was suggested by the authors that by involving CPS in the construction process, real-time monitoring and control of the construction process can be achieved. Moreover, tracking changes and updates and real-time information exchanges between the design office and job site can be facilitated using CPS integrated construction process (Akanmu & Anumba, 2015). Advancements in computation systems and automation are taking form in many ways such as IoT, IoS, and CPS. The inclusion of CPS increases the efficiency and productivity of the production process. However, there are still various challenges that surround the implementation

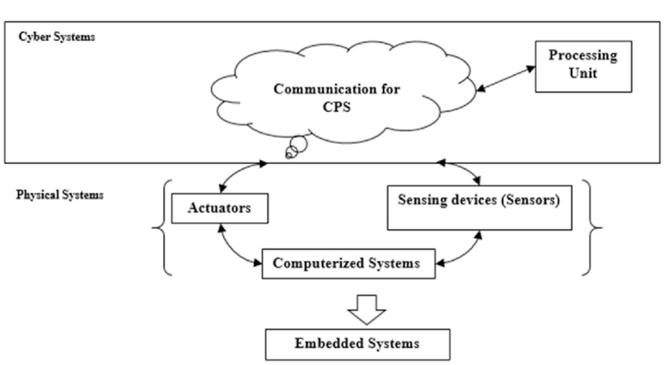

Fig. 1. The framework of Cyber-Physical Systems (CPS).

of CPS in the real world. In an interesting study to observe the challenges of a CPS integrated production system, a pick-and-place machine was chosen that solves a distributed version of the Towers of Hanoi puzzle. The system includes all the computational equipment such as a wireless network and concurrent computing resources coupled with the physical environment. The rationale for selecting the setup for investigating the challenges faced in a CPS coupled production process was the similarity of the issues that were faced by the industrial systems coming online with that of the pick and place machine. The major challenges that came to light in the study were collaborative control, feature interaction, multi-rate distributed architectures and an automated test evaluation approach combined with safety analysis (Mosterman & Zander, 2016).

2.2. Internet of things (IoT)

The Internet of things (IoT) is fundamentally a framework where information collection and exchange are facilitated between the physical objects connected to a communication network such as the Internet. This is accomplished with the use of sensors that are embedded in almost every physical device (Vijayakumar et al., 2019). The sensors collect the data from the devices such as information about temperature from the compressor in air conditioners, etc., and transmit it to the IoT platform where a detailed record of information from various devices is stored. The stored information or data is then analyzed using data analytics and useful information is extracted in the process. This information is then used by the experts, decision-makers, managers, and the public to make informed decisions thereby increasing the efficiency and productivity of the process (Kim et al., 2019). A great amount of work has been done in the field of implementing Industry 4.0 employing IoT in various domains including lean production, social networks, cloud computing, etc. Some of the notable recent articles published in this regard are listed below.

The aspects of the integration of the Industry 4.0 framework in lean production were studied with the perspective of understanding the co-existence of the framework and the lean production process. It was revealed that introducing Industry 4.0 using IoT has a strong potential of minimizing waste in the production process thereby yielding better quality products that add to the profitability of the organizations (Mrugalska & Wyrwicka, 2017). The prospects of residential buildings transitioning to smart homes were envisioned where the possibility of the generation of power within the household using own solar panels and wind turbines was postulated. Authors contended that by using IOT-enabled services, it will be possible to buy/sell energy from\to smart power grids (Stojkoska & Trivodaliev, 2017). IoT devices pose several challenges that need to be addressed to completely appreciate the technology. Among the most prominent ones are the interoperability challenges that can be classified into technical, semantic, and pragmatic. Technical challenges involve the glitch in the IoT devices' capability and protocols to co-exist and interoperate in the same computing paradigm. Semantic challenges concern the components of IoT that are responsible for the processing and interpretation of data. Lastly, pragmatic challenges include the behavioral aspect of the consumers where the intentions of the parties involved in the data transference and analysis are to be correctly and appropriately addressed (Yaqoob et al., 2017).

2.3. Smart factory

The IoT touches every facet of business today and the construction and manufacturing sector is no exception to it. According to Mckinsey and company (2019), the total economic impact of IoT by the year will be about $11.1trillion (Mckinsey, 2019). The National Institute of Science and Technology defines Smart Manufacturing as "Fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and customer needs" (NIST, 2019). In a typical manufacturing set-up, the central processing unit contains information about the finished product. The central processing unit then transfers stepwise instructions on the completion of the product or task to every module operating within the industry. Each time the instructions are executed, the product is sent back to the central unit for a quality check and further instructions. This cycle goes on till the last module is completed with the instructions for creating the final product. In the "smart factory", there is a decentralized control system, where the control is distributed between all the modules operating in the factory. They have instructions available to them via sensors and other communication networks and have the facility of mutual interaction among themselves (see Fig. 2). This way a lot of time is saved from detouring the entire path to the central unit and back to modules till the product is made. Industry 4.0 hinges on the concept of the smart factory. In the modular structured smart factories, CPS interacts with the physical world, monitors it, and creates a virtual copy that is capable of making decentralized decisions. With IoT, real-time information exchange takes place between CPS and humans thus facilitating an informed decision-making process that leads to enhanced productivity and efficiency (Hermann et al., 2016; Yeo et al., 2020). Many studies in the recent past have validated the effectiveness of the smart factory concept by the integration with IoT. In a study to demonstrate the measurement of manufacturing performance in real-time, IOT based performance model was created that operated in three stages. In the first, key performance indicators were identified to measure the overall equipment effectiveness followed by implementation of IoT-based architecture and performance measurement process using Business process modeling, and finally to validate the proposed model with a virtual factory. By simulation, the performance indicators were identified using the IoT-based framework (Hwang et al., 2017). Despite the advantages smart factory brings about in almost any discipline or domain, the inherent vulnerability of the IoT devices with limited resources and heterogeneous technologies together with the lack of adequate IOT standards makes smart framework a soft and easy target for cyber-attacks (Frustaci et al., 2018).

2.4. Recent studies highlighting challenges in the adoption of industry 4.0

In a study involving the integration of Industry 4.0 with a sustainable reverse logistics network, it was found that the major impediments in the adoption of Industry 4.0 include lack of sufficient expertise, lack of comprehension of Industry 4.0 framework, government's lack of enthusiasm and support (Pourmehdi et al., 2022). In another relevant study of the adoption of Industry 4.0 in the construction organization, it was suggested that the biggest obstacles to I4.0 adoption in construction projects are reluctance to change, a lack of clarity on the benefits and gains, and the expense of implementation. Data analysis revealed that, in terms of encouraging I4.0 adoption, the majority of construction organizations successfully manage the obstacles caused by a lack of standards, legal and contractual issues, and the cost of implementation (Cugno et al., 2021). The major barrier was revealed to be the enormous expenses associated with implementation and maintenance, closely followed by issues finding qualified candidates with the necessary skills. Other significant problems that impede the implementation of Industry 4.0 include severe layoffs, changes in compensation, and regulatory restrictions (Ozkan-Ozen & Kazancoglu, 2021). According to Kumar, Bhamu, & Sangwan, 2021, after a thorough review of the literature and the opinions of

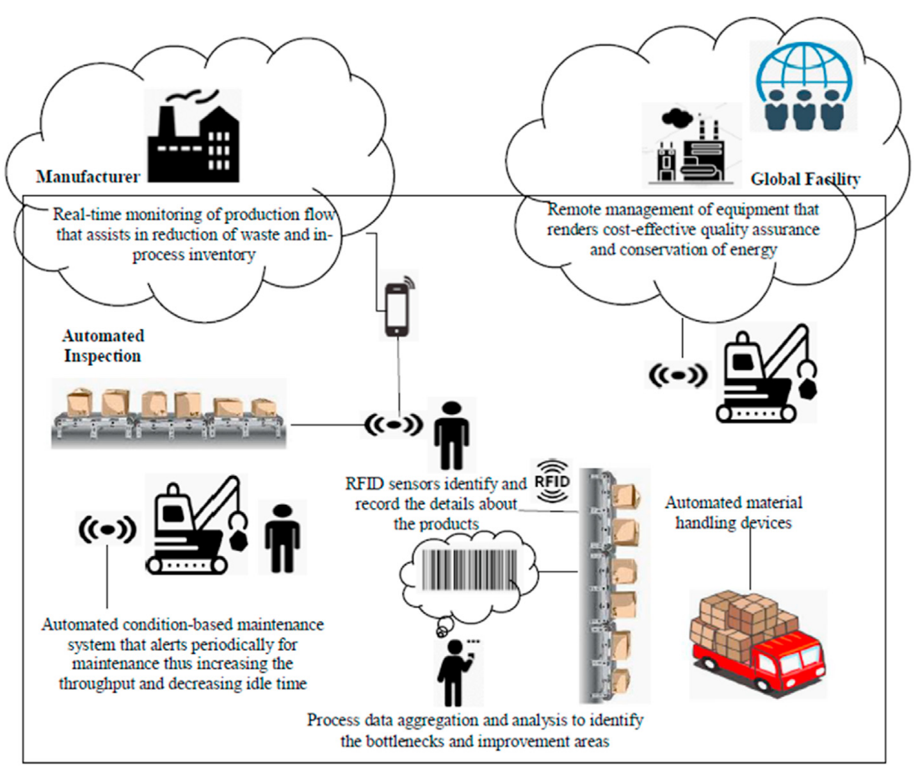

Fig. 2. Conceptualization of smart factory.

industry experts, the barriers identified in the implementation of Industry 4.0 in manufacturing organizations include poor value-chain integration, cyber-security issues, a lack of clarity regarding the economic benefits, a lack of workforce with the necessary skills, high investment requirements, a lack of infrastructure, job disruptions, issues with data management and data quality, a lack of security standards and norms, and resistance to change. In an attempt to manage the barriers in the implementation of Industry 4.0 in the textile and clothing industry it was discovered that the main obstacles include a lack of properly trained employees, a lack of understanding and dedication on the part of senior management, a lack of government support and laws, and subpar research and development, high implementation costs, failure-related anxiety, problems with smooth integration, and compatibility difficulties (Majumdar et al., 2021).

2.5. Research gaps

Reflecting on the extant literature on the adoption of Industry 4.0 in organizations, it is evident that the research on understanding the critical barriers in the implementation of the Industry 4.0 framework in the construction sector is relatively scanty. Additionally, the little research that exists on this subject does not involve Indian organizations. Thus, this study attempts to address the following research objectives:

- Identification of major factors that inhibit the adoption of Industry 4.0 in the Indian construction sector.
- Among the factors identified, which ones are the most critical and hence require immediate attention

The research questions answered in this study are as mentioned below:

- What are the major obstacles hindering the adoption of Industry 4.0 in Indian construction organizations?
- Prioritization of the major obstacles on the basis of degree of severity in the implementation of Industry 4.0 in Indian construction organizations.

To accomplish the research objectives a small-scale construction firm was selected in a remote part of Northern India. After personal interaction with the managers at the firm, it was found that the processes are not streamlined and mostly disorganized. It was indicated by the senior officials that it was not possible for the management to keep the track of all the processes simultaneously and hence frequent disruptions occurred in the production leading to loss of productivity. The firm, therefore, is poised to be a candidate where Industry 4.0 can be implemented to organize the activities and facilitate continuous monitoring that helps in increasing productivity.

2.6. Research contributions

The major contributions made through this article are as follows. The current study delves into the core operations of the construction sector of India to investigate the major obstacles in the way to adopting the Industry 4.0 data management framework. The work proposes a benchmarking framework that can be used to prioritize efforts to address the issue of non-adoption of new technologies in the construction sector of developing nations such as India. Additionally, this study uses a decision-making algorithm based on dominance-based rough sets that model the vagueness in the form of uncertainty and hesitancy in responding to survey-based studies.

Numerous studies are done in the field of adopting new technologies such as Industry 4.0 in the context of manufacturing industries (Ahmadi et al., 2020; Bag et al., 2021; Dixit et al., 2022; Kalsoom et al., 2021; Nimawat & Gidwani, 2022; Sharma et al., 2021; Tsai, 2021). The related study in the domain of the construction sector is fairly scanty. This work, therefore, is novel in its attempt to address the issue of factors responsible for the non-adoption of new technologies in the construction sector of developing nations. Also, the decision-making method based on Dominance based Rough sets is largely untouched when it comes to application in business problems. This enriches the existing literature on the availability of various MCDM tools in the business domain.

3. Research methodology

The paper investigates the challenges faced in the adoption or implementation of Industry 4.0 in the Indian construction industry and subsequently prioritizes them based on the magnitude of severity associated with them in the implementation process. The case study specifically focuses on the construction firms operating in the remote parts of Northern India where the scale of development is not very high. Also, with reference to the capital and workforce, the firms are classified as small-scale construction enterprises.

Based on the extant literature review and personal interaction with the construction management, IT professionals, and academicians, twenty-five challenges have been identified that prove to be the major hindrances in the adoption of the Industry 4.0 framework in the Indian construction industry. The literature was navigated using the keywords like Industry 4.0, challenges in IoT, smart factory, smart construction, obstacles in construction, technology barriers in construction, and the like (Kamble et al., 2018; Kergroach, 2017; Leitão et al., 2016; Muller et al., 2018; Preuveneers & Ilie-Zudor, 2017; Tortorella & Fettermann, 2018). The selection of construction management personnel, for the discussion about the challenges chosen for the study, was done purely based on the theoretical concept that they knew the readiness and capability of the firms to adopt new technology. The rationale for choosing them as decision-makers lies in the responsibilities they shoulder in the overall functioning of the organization. Top-level management is responsible for deriving broad strategic plans for the organization as a whole unit. Middle-level management comprising general managers, branch managers, and departmental managers are accountable to the top management for their department's functions and in most cases devote more time than the top management in executing organizational plans to achieve the objectives of top management. Lower managers are task or process-oriented and manage functional specialists and projects. IT professionals provided a better insight into the issues pertaining to the process of implementing the Industry 4.0 framework and the potential problems that can arise in case of a malfunction of the system. The IT experts are software developers with in-depth knowledge of the processes involved in the deployment of the new software frameworks. The academicians selected for the study were from the Department of Industrial and management engineering and construction disciplines that are active in the domain of integration of IoT in the construction sector. The academicians were the course instructors and research scholars who were researching various issues associated with the construction sector.

We can broadly classify the research methodology into three stages. In the first stage, the critical impediments to the adoption of Industry 4.0 in construction organizations were discovered by an extensive literature review. The impediments were cross-checked by the construction management for their appropriateness. We consulted the employees at the operations and technology/information level for their opinion about the impediments that were selected. The rationale for choosing the employees from the aforesaid levels was their experience and aptness for the nature of duties they perform at the construction sites. They suggested removing some impediments and including some new ones. For instance, we included challenges pertaining to "soft" attributes such as "unclear comprehension of Industry 4.0", "Need to establish a strong information collection, distribution, use, and management mechanism", and "Need to prepare for a significant organizational and process change". Many challenges were also discarded from the list after the discussions with the management on account of the redundancy or irrelevance in the context of the construction organizations. At the conclusion of the first stage, we were prepared with a list of impediments or challenges. In the second stage, pilot testing was conducted with a few respondents that were from different disciplines including construction, academicians, and information technology personnel. The wording of some challenges was changed in order to lend more clarity to the meaning. There were no major modifications in the challenges in the second stage. The third stage was marked by the collection of responses from the decision makers on the severity of the challenges in the adoption of Industry 4.0 in construction organizations.

There were disagreements between the three classes of experts on the inclusion of some of the considered challenges. However, the priority was given to the construction management over the two since they were involved in the construction activities directly. When all the experts felt a challenge was not very important to be included in the study, it was removed from the study. The final set of challenges and the description of the challenges proposed in the study is mentioned in Table 1.

3.1. Fundamentals of dominance-based Rough Set Analysis (DRSA)

The problem described above is a peculiar multi-criteria decision aiding (MCDA) problem and in particular, a class of MCDA problem: ranking. The technique employed for ranking in the present study is based on Rough Set theory (RST). In principle, RST is a knowledge discovery method that extracts information from the database by deciphering the specific patterns shown by the decision examples in the database (Pawlak, 1996). The study employs DRSA, an MCDA technique proposed by Greco, Matarazzo, and Slowinski (Fortemps et al., 2008; Greco, Matarazzo, Slowinski, & Stefanowski, 1999; Greco, Matarazzo, & Słowinski, 2001; Greco et al., 2000). Singh and Misra (2020) have considered this DRSA method for investigating employee perception of safety at the workplace and safety compliance. In addition, Błaszczyński et al. (2013) have applied the DRSA framework and variable consistency extension. Yang et al. (2008) mentioned the DRSA method and knowledge reductions to manage incomplete ordered information systems. Further, Zhai et al. (2009) employed the DRSA approach in product development while Liou and Tzeng (2010) proposed this approach to indicate customer behavior in the airline market. Moreover, Greco et al. (2007) have pointed out this approach as a proper way of handling graduality and Boggia et al. (2014) explained this method for assessing rural sustainable development potentialities. Roma et al. (2020) have discussed a consumer attitude analysis while Greco et al. (2008) figured out this method for interactive multi-objective optimization. DRSA is an extension of RST about reasoning from the decision situations involving ordinal evaluations of the objects from the experiment and the monotonicity between the evaluation criteria. The critical challenges are assigned values on the ordinal scale that follows the monotonic relationship that is "the higher the value the better is the assessment of the object". In the current study, the higher value implies Strong agreement suggesting the severity of the challenge and Strong disagreement signifies that the challenge or obstacle is not a very serious concern. The mathematical foundation of DRSA is the dominance principle that groups objects under study based on the dominance relationship between them. That is, objects valued higher than the others are grouped and the ones that are poorly valued form the other class of objects. The groups of objects generated using the principle of dominance form the basic information unit or granules of knowledge. These information units are then used in the generation or approximation of further elaborate information units that comprise the objects in the universe of discourse until all the objects are classified into one of the approximated classes. The reasoning from the approximated classes is done using the appropriate decision-making technique.

The traditional statistical tools employed in the decision-making process such as factor analysis, structural equation modeling, canonical correlation, and regression are hinged on an important theoretical underpinning – the normality assumption of the data. In real life, however, this is seldom true. For instance, if we talk about the current study, it takes the opinion data of a few experts. The data available to us, in this case, is far from normally distributed. The hypothesis testing procedures based on the traditional statistical tools require the normality assumption to formulate the statistics used to either accept or refute the hypothesis. This will not be feasible in the case where we have limited data to work with. The multi-criteria decision-making based on the Rough set theory does not require normality distribution of the data. This is an important relaxation made in the characteristics of the real-life data which in most cases is highly skewed and does not conform to the normality distribution. The second advantage offered by the decision-making algorithm based on the Rough set theory is the decision rules resulting from the application of the algorithm. These rules are in the form of "if – then – else" which are easy to understand and apply. Unlike the traditional statistical methods where results are obtained in terms of statistical values and p-values which is difficult to comprehend for people with no statistical background. This study uses DRSA for ranking the alternatives based on the rough set theory. The detailed processes of decision-making using DRSA are outlined in the subsequent sections.

3.2. Information table

The application of DRSA in the decision-making process needs the data to be laid out in a systematic matrix format. The set of "N" objects in the universe of discourse and the set of "M" criteria on which the objects are evaluated form the rows and columns respectively of the data matrix. For every object $n \in N$, there is a function "f" from "M" to "N" that assigns a value to every "N" for every "M" given by *f: M to N* such that to evaluate the two objects "n_1" and "n_2" it is sufficient to compare the functional values $f(n_1)$ and $f(n_2)$. The set of functional values is represented by the set V given by $\{v_{nm}\}$ for every n and m in the data matrix. The set of objects comprises the challenges in the adoption of Industry 4.0 and the criteria set is composed of the perspectives of the decision-makers in evaluating the severity of the challenges.

3.3. Pairwise comparison table (PCT)

The preferred set of objects N_P chosen for the study comprises the challenges that were consistently evaluated higher by all the decision-makers as shown in Table 2.

The principle underlying the ranking of objects is the pairwise comparison of objects i.e. assignment of the pairs of objects from the set N to *preference relation.* The basic case of preference relation is considered here, where there are two preference relations:

Table 1
Challenges in the adoption of Industry 4.0 in the Indian construction industry.

Code	Challenges in Industry 4.0 adoption	Explanation
C1	Heavy lay-offs due to smart processes	Recent advancements in the field of artificial intelligence and smart city have become a source of concern among experts regarding the complete obsolescence of human workers (Anakpo & Kollamparambil, 2021). This is particularly true in the context of the construction sector where most of the important tasks are accomplished with the assistance of people employed at various levels. With the inclusion of the Industry 4.0 integrated framework, tasks such as excavation, grading, and site work have the highest potential to be replaced by automated technologies based on the smart city concept (Smith, 2019). As per the report by PriceWaterhouseCoopers (PwC), in the construction sector, about 40% of the jobs will be replaced by automation (Kokina & Blanchette, 2019).
C2	Huge initial investment and maintenance costs	Integrating operational activities with new technology incurs large costs (Masood & Sonntag, 2020). Due to specific characteristics and complexities of the construction industry re-engineering of business processes in the light of the Industry 4.0 integrated framework requires high investments. From an economic point of view construction companies are hesitant to invest due to high cost which includes technical equipment investments and also training and education fees and infrastructure maintenance (Sharma et al., 2021).
C3	Need to prepare for a significant organizational and process change	The construction value chain involves several fragmented counterparts from all levels with diverse backgrounds to cater to the specific needs of the projects (Newman et al., 2020; Qi et al., 2021). This nature of the value chain makes the process of executing the Industry 4.0 framework a difficult one. Thus, despite the countless benefits offered by Industry 4.0 construction Industry is shown to exhibit reluctance to adopt the Industry 4.0 framework (Lekan et al., 2021).
C4	The requirement to attain advanced technical skills	The standards and processes involved in the integration of Industry 4.0 need to be revisited to suit the requirements of the construction Industry (Newman et al., 2020). The sophisticated equipment and devices required to execute Industry 4.0-driven operations will need advanced technical skills which present a challenge for the construction sector (Zabidin et al., 2020).
C5	Need to establish a strong information collection, distribution, use, and management mechanism	Changes within organizational processes due to the inclusion of the Industry 4.0 framework will entail changes in the execution process from the ground level (Saka & Chan, 2020). It is imperative to keep a detailed record of the important information pertaining to the execution and maintenance of operations. Due to the highly scattered nature of activities in the construction sector, consolidating information about every department at the granular level is a challenge.
C6	Lack of management support	Construction companies mainly operate using traditional methods involving humans and basic machinery. To educate the employees at all the levels of the hierarchy management has to take the necessary steps to organize seminars, workshops, and one-to-one discussion sessions. Sensitization of people working in construction firms to Industry 4.0 or any other new technology is essential for the adoption. Management involvement and support are, therefore, an urgent need to empower the construction Industry with new technology (Abdul-Hamid et al., 2020).
C7	The problem in hiring qualified professionals, especially at the ground level	The majority of the workforce in the construction sector are the ones employed at the ground level with no to very little educational background. These workers perform activities such as carrying bricks or heavy material from one place to another, digging, excavating, painting, etc. It is a challenge to introduce the concept of Industry 4.0 or automation to them as understandably they will not be able to feel comfortable around technical terms (Rana et al., 2021).
C8	Reluctance and apprehensions to resort to change in technology	Industry 4.0 is a new technology that requires an understanding of analytical, programming, and technical knowledge. Clearly, workers who have been working with the traditional methods will find it difficult to adjust to a new method of operating (Wagire et al., 2021).
C9	Need to establish research and development facilities	Understanding the concept of Industry 4.0 entails a thorough knowledge of the underlying phenomena of CPS, smart factories, and IoT. Setting up research and development departments to foster the learning of the concepts is a costly investment for construction firms especially when the return on investment is highly uncertain (Kumar, 2016).
C10	Educating higher management particularly experienced professionals about the technological change	Management in the construction sector lacks a clear understanding of the impact the future digitization and automation will have on the skill requirement. Even HR will not be adequately equipped to execute strategies to address emerging skill gaps (Bag & Pretorius, 2022).
C11	Providing contractors and sub-contractors the necessary skills and understanding of the process	The construction supply chain involves many participants in the production process. Incorporating a new technical framework based on industry 4.0 necessitates proper briefing and education for all the supply chain participants to completely understand the new technology (Sepasgozar, 2020).
C12	Recruitment of skilled personnel to impart necessary knowledge and training to the employees	Systematic orientation of existing and new employees to sensitize them to the new technical framework requires experienced personnel with a strong technical background. This is perceived to be a challenge as educating the ground-level workers at the construction firm with little or no education will find it difficult to assimilate the technical concepts related to Industry 4.0 (Masood & Sonntag, 2020).
C13	Non-seriousness to adopt the new concepts in technology	Senior management in the construction sector of India has been acclimatized with the traditional methods of operating. It is a challenge to convince them to switch to advanced methods of operations particularly when it requires them to start learning from scratch (Li et al., 2020).
C14	Unclear about the economic benefits of IoT-enabled framework	With the inclusion of new technology, there is a huge investment. It takes some time to generate cash flows. The uncertainty associated with the actual starting point to generate profits makes management skeptical about the adoption of Industry 4.0 (Abdul-Hamid et al., 2020).
C15	Getting a common consensus on the adoption of new technology from the employees and management	Unless there is a unanimous agreement across all the departments to adopt the new technology it cannot be deployed to its full capacity in any organization. This is so because in the construction sector or any other organization departments operate in a well-integrated fashion. So if there is a disconnect at any point in the supply chain the framework based on new technology cannot be integrated into the organization (Gupta et al., 2021).
C16	Unclear comprehensibility of the advantages of IoT	Industry 4.0 is still in its infancy when it comes to the construction sector of India. The economic benefits resulting from the adoption of Industry 4.0 is still uncertain to various stakeholders. It is a challenge to clearly lay out the advantages Industry 4.0 brings to the sector both in terms of the economic and social points of view of the organization (Chavez et al., 2021).
C17	Disruptions in the compensation policies	

(*continued on next page*)

Table 1 (*continued*)

Code	Challenges in Industry 4.0 adoption	Explanation
		Industry 4.0 has the potential of redesigning the entire landscape of activities in any organization including the compensation of the employees. Naturally, when operations go automatic with little or no manual intervention the payment made to the employees will also change. An extensive revamping will be needed from the management part to rethink the compensations made to the employees (Khanzode et al., 2021).
C18	Proper internet connectivity and other IT facilities	Sophisticated infrastructure is a challenge for the implementation of the Industry 4.0 framework in the construction sector of developing nations such as India. Small construction firms are established in remote regions of India where internet connectivity is scarce and resources are limited (Chauhan et al., 2021).
C19	Uncertain impact on working life	Skepticism regarding work-life balance is strongly felt when new technology is deployed in the workplace. Employees foresee a lot of man-hours being put in to first understand the new system and technology and secondly to actually operate those (Narayanamurthy & Tortorella, 2021).
C20	Safety issues arising due to manhandling of devices	Industry 4.0 integrated framework involves the use of sophisticated technical components which are required to be used very delicately. For instance, the equipment needs to be handled with extreme precision or else it might malfunction or simply get damaged (Sharma et al., 2021).
C21	Increased protection of sensitive devices from dust and pollutants present on-site	The devices that are used for the deployment of Industry 4.0 are extremely sensitive devices. These devices are supposed to be kept in an absolutely clean and dust-free atmosphere. Finding clean places in construction firms is fairly challenging (van Lopik et al., 2020).
C22	Need to establish a reliable and stable machine-to-machine communication network	Industry 4.0 would require every channel member to be integrated for effective transmission of information across every department. Thus, digital infrastructure is a pivotal issue that needs attention at a detailed level. As per the research conducted by (Bag et al., 2021) lack of infrastructure has been cited as one of the major impediments to the adoption of Industry 4.0.
C23	Need to ensure proper monitoring, inspection, and validation of services in the production of key assets	With the adoption of Industry 4.0 in the construction sector, various operations across all the divisions in and outside the firm will undergo a paradigm change in the form of execution of tasks and producing the output. In such a situation, careful monitoring will be called for on an extensive scale. This can challenge the management and workers to operate concurrently (Mastos et al., 2020).
C24	Lack of regulation, standards, and certifications	Small and medium enterprises have apprehensions regarding the adoption of Industry 4.0 due to the lack of proper regulations, certifications, and standards. With the rapidly changing technological landscape, regulators are continually challenged to form standards and regulations to safeguard the interests of the customers (Raj et al., 2020).
C25	Legal barriers	The efforts to adopt Industry 4.0 are impeded by the lack of proper legislative measures for the growth of cyber security, cloud computing, augmented reality, and artificial intelligence in developing nations such as India (Kumar, Raut, et al., 2021).

Table 2
Preference ordered set of challenges.

S.N.	Preference ordered a set of challenges from most severe to least severe
1	C2
2	C7
3	C20
4	C21
5	C24
6	C1
7	C4
8	C17

Comprehensive outranking (CO) and comprehensive non-outranking (CNO) relations. For instance, from Table 2 the ranks given by the decision-maker are as follows: C2, C7, C20, C21, C24, C1, C4, and C17. This means that pairs (C2, C7) ∈ CO, (C7, C20) ∈ CO, (C20, C21) ∈ CO, (C21, C24) ∈ CO, (C24, C1) ∈ CO, (C1, C4) ∈ CO, (C4, C17) ∈ CO and (C7, C2) ∈ CNO, (C20, C7) ∈ CNO, (C21, C20) ∈ CNO, (C20, C7) ∈ CNO, (C21, C20) ∈ CNO, (C24, C21) ∈ CNO, (C1, C24) ∈ CNO, (C4, C1) ∈ CNO, (C17, C4) ∈ CNO; where (C2, C7) ∈ CO means that C2 is at least as severe as C7, likewise (C7, C2) ∈ CNO implies that C7 is NOT at least as severe as C2.

The pairwise comparisons of objects form the foundation of the Pairwise comparison table (PCT). Since the attributes or the column vectors are ordinal valued, the ordered pair of evaluations are depicted in Table 3. It shows a portion of the pairwise comparison of the objects.

Table 3 represents the ordinal classification of the challenges where the attributes comprise condition attributes and a decision attribute. The decision attribute is the outranking relation. This table acts as input preference information that is analyzed by DRSA.

3.4. Approximating dominance relations using rough approximation

As mentioned in Section 3.1, RST and DRSA carry out the reasoning in the decision-making problem using the basic information unit called granules of knowledge. The dominance cones act as granules of knowledge in DRSA.

For the ordinal scaled attribute set “M”, the pair of an object $(x,y)\varepsilon N$ is said to dominate $(w,z)\varepsilon N$ if (Kusunoki et al., 2021),

$$f_m(x) \geq f_m(w) \cup f_m(y) \leq f_m(z)\, \forall m \quad \varepsilon \quad M \tag{1}$$

Where ≥ is the weak preference relation and ≤ is the weak inverse preference relation?

Symbolically (1) is represented as

$$(x,y) \quad D_M \quad (w,z)$$

The granules of knowledge for approximation in DRSA are formulated as shown below.

1. The set of objects dominating $(a,b) \quad \varepsilon \quad N_P$ are given by the M-dominating set as (Greco et al., 2007),

$$D_M^+(w,z) = ((c,d) \quad \varepsilon \quad N_P \times N_P : (c,d)D_M(a,b))$$

2. Set of objects dominated by $(a,b) \quad \varepsilon \quad N_P$ are given by the M-dominated set as (Greco et al., 2007),

$$D_M^-(w,z) = ((c,d) \quad \varepsilon \quad N_P \times N_P : (a,b)D_M(c,d))$$

The pair of objects (x,y) is said to be consistent if they are assigned to CO as compared to (w,z) that are assigned to CNO, given (x,y) − M dominates (w,z). Otherwise, (x,y) constitutes an

Table 3
Pairwise comparison table (PCT) of the preferred set of objects.

	D1 pair (+)	D2 pair (+)	D3 pair (+)	D4 pair (+)	D5 pair (+)	D6 pair (+)	D7 pair (+)	D8 pair (+)	D9 pair (+)	Relation
C2, C2	4, 4	5, 5	4, 4	5, 5	4, 4	4, 4	5, 5	5, 5	4, 4	CO
C2, C7	4, 5	5, 4	4, 4	5, 4	4, 5	4, 4	5, 5	5, 5	4, 4	CO
C2, C20	4, 5	5, 4	4, 4	5, 4	4, 5	4, 4	5, 4	5, 4	4, 4	CO
C2, C21	4, 5	5, 4	4, 4	5, 5	4, 5	4, 4	5, 4	5, 5	4, 5	CO
C2, C24	4, 5	5, 4	4, 4	5, 5	4, 4	4, 4	5, 4	5, 4	4, 5	CO
C2, C1	4, 4	5, 5	4, 4	5, 5	4, 5	4, 4	5, 4	5, 3	4, 4	CO
C2, C4	4, 5	5, 5	4, 3	5, 4	4, 5	4, 4	5, 4	5, 5	4, 4	CO
C2, C17	4, 4	5, 5	4, 3	5, 5	4, 5	4, 4	5, 4	5, 4	4, 5	CO
C7, C2	5, 4	4, 5	4, 4	4, 5	5, 4	4, 4	5, 5	5, 5	4, 4	CNO
C7, C7	5, 5	4, 4	4, 4	4, 4	5, 5	4, 4	5, 5	5, 5	4, 4	CO
C7, C20	5, 5	4, 4	4, 4	4, 4	5, 5	4, 4	5, 4	5, 4	4, 4	CO
C7, C21	5, 5	4, 4	4, 4	4, 5	5, 5	4, 4	5, 4	5, 5	4, 5	CO
C7, C24	5, 5	4, 4	4, 4	4, 5	5, 4	4, 4	5, 4	5, 4	4, 5	CO
C7, C1	5, 4	4, 5	4, 4	4, 5	5, 5	4, 4	5, 4	5, 3	4, 4	CO
C7, C4	5, 5	4, 5	4, 3	4, 4	5, 5	4, 4	5, 4	5, 5	4, 4	CO
C7, C17	5, 4	4, 5	4, 3	4, 5	5, 5	4, 4	5, 4	5, 4	4, 5	CO
C24, C4	5, 5	4, 5	4, 3	5, 4	4, 5	4, 4	4, 4	4, 5	5, 4	CO
C24, C17	5, 4	4, 5	4, 3	5, 5	4, 5	4, 4	4, 4	4, 4	5, 5	CO
C1, C2	4, 4	5, 5	4, 4	5, 5	5, 4	4, 4	4, 5	3, 5	4, 4	CNO
C1, C7	4, 5	5, 4	4, 4	5, 4	5, 5	4, 4	4, 5	3, 5	4, 4	CNO
C1, C20	4, 5	5, 4	4, 4	5, 4	5, 5	4, 4	4, 4	3, 4	4, 4	CNO
C1, C21	4, 5	5, 4	4, 4	5, 5	5, 5	4, 4	4, 4	3, 5	4, 5	CNO
C1, C24	4, 5	5, 4	4, 4	5, 5	5, 4	4, 4	4, 4	3, 4	4, 5	CNO
C1, C1	4, 4	5, 5	4, 4	5, 5	5, 5	4, 4	4, 4	3, 3	4, 4	CO
C1, C4	4, 5	5, 5	4, 3	5, 4	5, 5	4, 4	4, 4	3, 5	4, 4	CO
C1, C17	4, 4	5, 5	4, 3	5, 5	5, 5	4, 4	4, 4	3, 4	4, 5	CO
C4, C2	5, 4	5, 5	3, 4	4, 5	5, 4	4, 4	4, 5	5, 5	4, 4	CNO
C4, C7	5, 5	5, 4	3, 4	4, 4	5, 5	4, 4	4, 5	5, 5	4, 4	CNO
C17, C20	4, 5	5, 4	3, 4	5, 4	5, 5	4, 4	4, 4	4, 4	5, 4	CNO
C17, C21	4, 5	5, 4	3, 4	5, 5	5, 5	4, 4	4, 4	4, 5	5, 5	CNO
C17, C24	4, 5	5, 4	3, 4	5, 5	5, 4	4, 4	4, 4	4, 4	5, 5	CNO
C17, C1	4, 4	5, 5	3, 4	5, 5	5, 5	4, 4	4, 4	4, 3	5, 4	CNO
C17, C4	4, 5	5, 5	3, 3	5, 4	5, 5	4, 4	4, 4	4, 5	5, 4	CNO
C17, C17	4, 4	5, 5	3, 3	5, 5	5, 5	4, 4	4, 4	4, 4	5, 5	CO

inconsistent pair of an object. The lower and upper approximations of CO and CNO are given as follows.

The D-lower approximation of CO, represented as $\underline{D(CO)}$, and the D-lower approximation of CNO symbolized as $\underline{D(CNO)}$ and are given as follows (Greco, Matarazzo, & Słowinski, 1999),

$$\underline{D(CO)} = (x,y) \quad \varepsilon \quad N : (D^{+}(x,y) \subseteq CO)\underline{D(CNO)} = (x,y) \quad \varepsilon \quad N : (D^{-}(x,y) \subseteq CNO) \tag{2}$$

The D-upper approximation of CO, represented as $\overline{D(CO)}$, and the D-upper approximation of CNO symbolized as $\overline{D(CNO)}$ and are given as follows (Greco, Matarazzo, & Slowinski, 1999),

$$\overline{D(CO)} = \bigcup_{(x,y)\ \varepsilon\ CO} D^{+}(x,y)\overline{D(CNO)} = \bigcup_{(x,y)\ \varepsilon\ CNO} D^{-}(x,y) \tag{3}$$

The D-boundary of CO, denoted by (CO), and the D - boundary of CNO, denoted by $BD(CNO)$ are given by (Greco, Matarazzo, Slowinski, & Stefanowski, 2000),

$$BD(CO) = \overline{D(CO)} - \underline{D(CO)}BD(CNO) = \overline{D(CNO)} - \underline{D(CNO)} \tag{4}$$

3.5. Decision rules

The rough approximation of the dominance relation, as mentioned in the previous section, gives more comprehensibility and perspective to the reasoning process by elaborately describing the elements in the PCT in the form of *decision rules.* The rules are in the natural language form of "If .....then", where the antecedents are the conjunction of the condition attributes and the consequents are the disjunction of the decision variables. Essentially, there are five classes of decision rules. Two pertain to the *certain* and *possible* classes of outranking (CO) relation and the other two are the *certain* and *possible* classes of non-outranking (CNO) relation. There are also *approximate* decision rules, ones that can be grouped in either of the two relations. The utility of the decision rules lies in their interpretive capability of the problem under consideration. C*ertain* rules represent exact knowledge whereas *possible* rules denote the possible knowledge about the information system. The *approximate* decision rules represent knowledge that is doubtful since they are supported by inconsistent pairs of objects only (Blaszczynski, Roman, & Szeląg, 2011; Błaszczynski, Słowinski, & Szelag, 2009). The decision rules for the present study are shown in Table 4.

The following characteristics indicate the quality (efficiency) of the decision rules. For a decision rule "*h*"

- *Support (h):* the number of pairs of objects N_P that support *h.*
- *Strength (h):* Ratio of Support (h) and the total number of objects in N^P i.e.

$$\frac{Support(h)}{|N_P|}$$

- *Coverage (h):* Ratio of Support (h) and the number of objects that comply with the relationship established in *h*

The decision rules yielded by the DRSA algorithm add value to the decision-making process by establishing an easily

Table 4
Minimal decision rules obtained using VC DOMLEM algorithm.

Decision rule (r)	coverage factor (r)	Strength (r)
#Certain at least rules		
1: {PAIR(D3) D (4,3)} then x CO Y	0.33	0.19
2: {PAIR(D1) D (5,5)} & {PAIR(D3) D (3,3)} then x CO Y	0.28	0.16
3: {PAIR(D1) D (4,4)} & {PAIR(D3) D (3,3)} then x CO Y	0.22	0.13
4: {PAIR(D2) D (5,5)} & {PAIR(D7) D (5,5)} then x CO Y	0.22	0.13
5: {PAIR(D2) D (4,4)} & {PAIR(D7) D (5,5)} then x CO Y	0.22	0.13
6: {PAIR(D3) D (4,4)} & {PAIR(D8) D (3,3)} then x CO Y	0.17	0.09
7: {PAIR(D3) D (4,4)} & {PAIR(D5) D (4,4)} & {PAIR(D8) D (4,4)} then x CO Y	0.14	0.08
#Certain at most rules		
8: {(3,4) D PAIR(D3)} then x CNO Y	0.43	0.19
9: {(4,5) D PAIR(D7)} then x CNO Y	0.43	0.19
10: {(4,4) D PAIR(D3)} & {(3,4) D PAIR(D8)}then x CNO Y	0.18	0.08
11: {(4,5) D PAIR(D1)} & {(3,3) D PAIR(D3)} then x CNO Y	0.18	0.08
12: {(4,5) D PAIR(D2)} & {(5,5) D PAIR(D7)} then x CNO Y	0.14	0.06
13: {(4,4) D PAIR(D3)} & {(4,5) D PAIR(D5)} & {(4,4) D PAIR(D8)} then x CNO Y	0.11	0.05

comprehensible reference for the decision-makers to assess the evaluation process. Thus, rule number 1 states that if the decision-maker D3 rates alternatives x and y as 4 and 3 respectively then “x is at least as good as y”. Along similar lines, rule number 11 states that if x and y are evaluated as 4 and 5 from D2, 3, and 3 by D3 then “x is NOT at least as good as y”. The decision rules with a high value of coverage and strength indicate a higher degree of confidence in that rule. This is so because a higher coverage implies a large number of objects in the dataset are complying with the decision rule. Hence, the rule can be applied for a more generalized inference about the population. Leaning on the aspect of better generalizability, considering the coverage of more than 25%, it is found that rules 1, 2, 8 and 9 can be utilized for making reasonably accurate decisions for the population. Thus, if decision-makers D1 and D3 consider a challenge to be highly severe, immediate attention is needed to analyze the challenge as it potentially can interfere with the successful implementation of Industry 4.0. Similarly, rules 8 and 9 insinuate the importance of decision-maker D7 in establishing the severity of a challenge in the adoption of the Industry 4.0 framework.

3.6. Preference graphs and ranking

The decision rules discovered in section 3.5 establishes the relationship between the objects in the set $N_P \times N_P$. The set N_P, however, contains a selected number of objects from the set N. That is the objects that are considered for inducing the preference information in the decision-making process. The set of decision rules is used to generate the preference graphs that depict the outranking and non-outranking relations between all the objects in the set N. Fig. 3 shows the preference graph for the current study.

The nodes of the graph are the objects i.e. challenges considered for the study and the arcs represent the comprehensive CO and CNO relations between the objects. Specifically, green arcs stand for CO and red arcs denote CNO. The final ranking of the objects is performed using the Net Flow Score (NFS) method. The number of total green arcs net of a total number of red arcs to a given object yields a net flow score number for the object. The object with the highest NFS is given the top ranking followed by objects with low NFS (Szeląg et al., 2010).

4. Results and discussion

The final ranking (weak order) of the challenges based on the net flow score (NFS) method is shown in Table 5.

From Table 5, “Huge initial investment and maintenance costs (C2)” acquire the highest rank followed closely by “Problem in hiring qualified professionals, especially at the ground level (C7)”, “Safety issues arising due to manhandling of devices (C20)” and “Increased protection of sensitive devices from dust and pollutants present on-site (C21)”, “Need to ensure proper monitoring, inspection and validation of services in the production of key assets (C23)”, “Lack of regulation, standards and certifications (C24)” and “Getting a common consensus for the adoption of new technology from the employees and management (C15)”. Among the less severe challenges, notable ones are “Providing contractors and subcontractors the necessary skills and understanding of the process (C11)”, “Proper internet connectivity and other IT facilities (C18)”, “Heavy lay-offs due to smart processes (C1)”, “Need to prepare for a significant organizational and process change (C3)”, “Need to establish a strong information collection, distribution, use and management mechanism (C5)”, “Recruitment of skilled personnel to impart necessary knowledge and training to the employees (C12)” and “Need to establish a reliable and stable machine to a machine communication network (C22)”. Factors that poised as relatively tractable and not so challenging in the adoption of Industry 4.0 framework also indicated by the negative NFS were “Educating higher management particularly experienced professionals about the technological change (C10)”, “Unclear about the economic benefits of IoT enabled framework (C14)”, “Uncertain impact on working life (C19)”, “Requirement to attain advanced technical skills (C4)”, “Need to establish research and development facilities (C9)”, “Unclear comprehensibility of the advantages of IoT (C16)”, “Non-seriousness to adopt the new concept in technology (C13)”, “Disruptions in the compensation policies (C17)”, “Lack of management support (C6)”, “Reluctance and apprehensions to resort to change in technology (C8)” and “Legal barriers (C25)”.

The results suggest that the major impediment to the adoption of Industry 4.0 in the Indian construction sector is the huge investment and costs to set up the data management framework. The construction sector of India still focuses on traditional methods for its operations and other logistics. Also, this sector is under tremendous financial stress owing to low productivity vis-à-vis other sectors such as manufacturing. It is a challenge for the management to think beyond what is considered a norm and invest in new technologies that can help this sector to resurrect. The data management framework based on industry 4.0 involves sophisticated computers with high processing power and continuously running broadband internet connectivity. This requires a huge financial and intellectual investment which the sector is skeptical to arrange for. Industry 4.0 technology deployment is expensive. These technologies have expensive ownership, operation, and management costs. Some technological advancements are still in the early stages of development. Such technologies go through

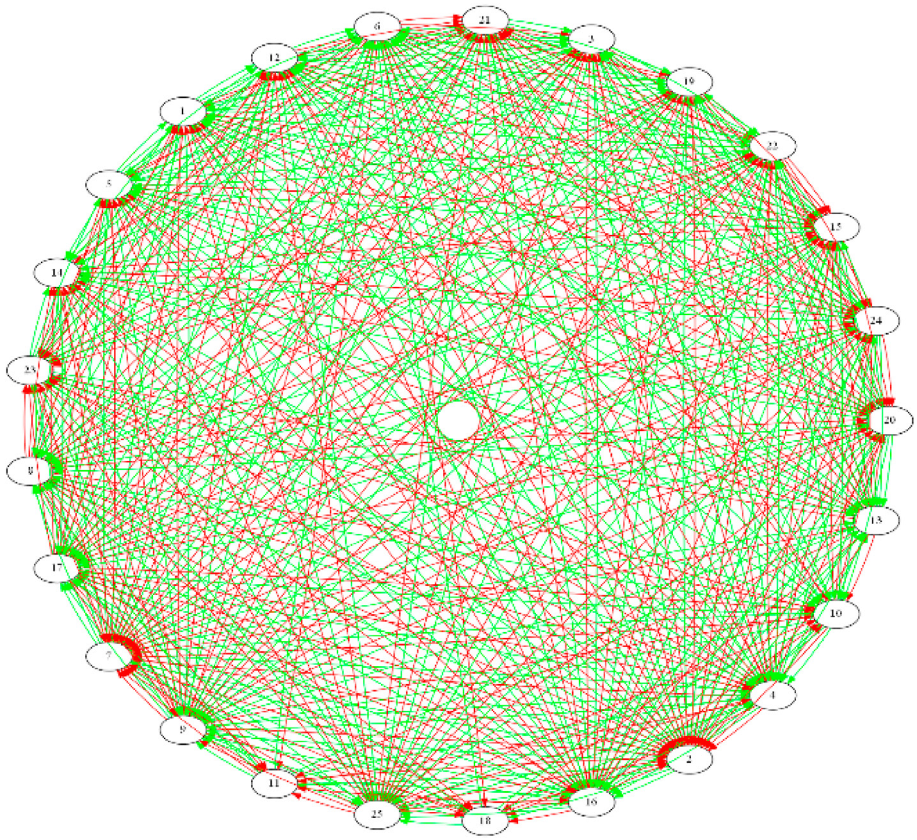

Fig. 3. Preference graph of the objects in the set N.

Table 5
Final ranking of Safety Indicators based on Net Flow Score (NFS) method.

Challenges	Final Rank	Net Flow Score
C2	1	48
C7	2	44
C20, C21	3	32
C23	4	28
C24	5	25
C15	6	23
C11, C18	7	12
C1, C3, C5, C12, C22	8	5
C10, C14, C19	9	−3
C4, C9, C16	10	−25
C13, C17	11	−37
C6, C8, C25	12	−41

constant development. Thus, it may be expensive to regulate the use of such technology. The worry of an uncertain return on investment makes this situation worse. Along with these problems, there are also the costs associated with technical equipment training. The training may also make it necessary to engage a coach for the current personnel, raising the expense of implementation. This finding reinforces much of the literature (Kamble et al., 2020; Sharma et al., 2021).

The challenges that were ranked higher are the ones that need immediate attention from the management of the firms interested in incorporating new technologies. Clearly, finding skilled and experienced people, particularly the ones at the basic level is one factor that should be attended to with extreme care. Since Industry 4.0 is a new technology with state-of-the-art architecture it requires an in-depth knowledge of handling the framework. This means that hiring people with the apt knowledge of the software is needed. The skillset required to operate on computers and various machine learning algorithms in order to accomplish the objective will be difficult and expensive to obtain. Also, the management has to make arrangements for the personnel employed to handle the computer systems on-site for better monitoring of the systems in case of an unexpected event. This will again lead to costs that the organizations will have to incur. The main obstacle to digital transformation is frequently identified as access to skills. Adopters of new technologies say it's hard to find, train, and reskill people, especially in the fields of user interface, data science, software development, and machine-level controls. In some cases, issues with technology accessibility arise from people who are unwilling to use new digital tools and applications or who find them to be too challenging. If your company is concerned about this, conducting a training needs analysis to establish what training your workers might want may be helpful. This finding is consistent with Masood and Egger (2019).

Among the factors that posed serious challenges for the adoption of Industry 4.0 was gaining the consensus from all the stakeholders to go ahead with the integration of new technology with the operational activities of the construction firm. This is particularly important where the daily operations are carried out in a coherent way involving various departments. Incorporating new technology in such situations will entail convincing every department about its advantages of it. In developing nations such as India, convincing people to adopt new technology is a daunting task because they have become used to working in the traditional framework, and opting to think out of the box clearly pulls them out of their comfort zone (Afolayan & de la Harpe, 2020). Senior management and seasoned workers will find it particularly difficult to adjust to the new method of operations based on Industry 4.0 and thus will be the major source of resistance to the implementation in the construction sector. The nature of work in this sector is mostly physical and also distributed across several smaller departments. With the inclusion of Industry 4.0 massive reform in the operational activities and supply chain ecosystem is inevitable. Continuous support from the workforce will be required in order to sustain the framework based on new technologies. Successfully managing culture change is essential to Industry 4.0, but if done poorly, it could become a barrier. Your employees may be unable to adapt, hesitant, or resistant if they are not prepared for the changes. The success of any digital initiative depends on getting their support and preparing them for the technology change. The cultural shift required for digital transformation can be brought about through leadership and top-down leadership.

The adoption of new technology such as Industry 4.0 in the construction sector is hindered due to the lack of standards and certifications in the process of implementation. The lack of standards encompasses the need for technology standards and process standardization. Industry 4.0 is hindered by the lack of rules and operating procedures in developing countries as well as by the absence of effective legislative measures to support the development of technologies like augmented reality, cloud computing, artificial intelligence, and cyber security.

The construction sector of India, being highly diverse in terms of the kind of activities undertaken across various levels, poses a challenge in standardizing the data management framework based on Industry 4.0. This observation is consistent with Setyaningsih et al. (2020). Among the less severe challenges were getting proper internet connectivity, lay-offs due to disruption in the technology, and maintenance of an information distribution and management mechanism. The reason these challenges are considered less severe as compared with the aforementioned lies in the chronology of the occurrences. For instance, if the organization is able to receive the standards and certifications to incorporate the Industry 4.0 framework then getting proper internet connectivity is the logical next step. Heavy lay-offs due to smart processes substituting manual workforce is a definite outcome that every organization implementing a new technology framework such as Industry 4.0 needs to prepare for. The above findings are reinforced by similar studies done across various sectors in Masood & Sonntag, 2020; Kumar, 2016; Abdul-Hamid et al., 2020.

The following section presents the results of the sensitivity analysis performed for six different scenarios each comprising a different subset of decision-makers.

4.1. Sensitivity analysis

The process by which the sensitivity of the ranking (weak order) of the alternatives for different sets of criteria (perspectives) is assessed is termed sensitivity analysis. The different sets of criteria are represented by scenarios S-1, S-2, S-3, S-4, S-5, and S-6. The scenarios are distinguished based on the decision-makers from different domains. The current study includes the evaluation of each challenge from three different perspectives namely Information technology (IT), Academics (AC), and Construction Management (CM). The composition of various scenarios is shown below. S-1: IT, S-2: AC, S-3: CM, S-4: IT & AC, S-5: AC & CM, and S-6: IT & CM. The results of the analysis are summarized in Table 6.

The normalization of the ranks was done in order to confine the ranks of the challenges in the interval (0,1]. This was necessary to enable comparison among the challenges where the highest ranks were different for different scenarios. The last column of the table shows the number of times a particular challenge was evaluated as the major threat or obstacle in the implementation of Industry 4.0 across the six scenarios. The normalized ranks above 0.6 were considered a significantly higher rank and thus the corresponding challenge was regarded as a major threat.

The challenges that were considered severe across all the scenarios were the “Need to establish a strong information collection, distribution, and use and management mechanism (C5)”, “Lack of management support (C6)”, and “Need to establish research and development facilities (C9)”, “Providing contractors and subcontractors the necessary skills and understanding of the process (C11)”, “Recruitment of skilled personnel to impart necessary knowledge and training to the employees (C12)”, “Non-seriousness to adopt the new concept in technology (C13)”, “Unclear about the economic benefits of IoT enabled framework (C14)”, “Unclear comprehensibility of the advantages of IoT (C16)”, “Uncertain impact on working life (C19)” and “Need to establish a reliable and stable machine to a machine communication network (C22)”.

The ranks obtained using sensitivity analysis are shown remarkable differences from the ranks in Table 6. This can be attributed to the difference in the perspectives of various domains considered in the study. For instance, a threat of higher magnitude is perceived from challenge C5 by IT personnel as opposed to challenging C12 which is considered a bigger challenge for the management. The graphical representation of sensitivity analysis is shown in Fig. 4.

5. Implications

5.1. Theoretical implications

The literature review and consultation with experts from the construction industry and academicians identified key challenges in the adoption of Industry 4.0 in the construction sector of developing nations such as India. The literature related to exploring challenges in the adoption of new technologies such as Industry 4.0 in the construction sector in India is scanty. This study adds to the existing literature firstly by incorporating the information about the hurdles impeding the propensity of the management of the construction sector to venture into the realm of new technology. Secondly, the method of ranking based on Dominance-based Rough sets employed in this study is a relatively unexploited area in the domain of multi-criteria ranking problems. This should enrich the field of multi-criteria decision-making that integrates Rough sets with multi-criteria decision-making problems.

5.2. Managerial implications

This empirical work on investigating the challenges in the adoption of the Industry 4.0 framework in the Indian construction industry and subsequently prioritizing them based on the magnitude of severity is expected to add considerable value to the existing literature. It offers a framework that can be utilized to identify critical barriers in the establishment of the IoT-enabled work processes and is an effective tool to benchmark against competitors as well. The major take-a-ways from the current work are listed below:

- From a theoretical point of view, this exploratory study proposes 25 challenges/obstacles in embracing Industry 4.0 framework in the Indian small-scale construction industry. The factors identified as the most critical are the ones that need immediate attention in order to advance technologically leading to increased productivity.
- The study presents a detailed discussion on the identification of the challenges in the implementation of Industry 4.0. In the process, the interdependency between several challenges can

Table 6
Sensitivity analysis table.

	S - 1	S - 2	S - 3	S - 4	S - 5	S - 6	# number of times ranked higher (normalized value greater than 0.6)
C1	0.2	0.1	0.7	0.1	0.5	0.3	1
C2	0.2	0.3	0.2	0.3	0.1	0.1	0
C3	0.1	0.1	0.7	0.1	0.5	0.6	2
C4	0.5	0.2	0.3	0.2	0.3	0.4	0
C5	**0.2**	**0.6**	**0.7**	**0.8**	**0.6**	**0.9**	**5**
C6	**0.9**	**0.1**	**0.8**	**0.6**	**0.5**	**0.9**	**4**
C7	0.2	0.2	0.2	0.5	0.3	0.2	0
C8	0.7	0.1	0.5	0.4	0.2	0.8	2
C9	**0.5**	**0.6**	**0.7**	**0.5**	**0.6**	**0.8**	**4**
C10	0.2	0.4	1.0	0.5	0.8	0.9	3
C11	**0.4**	**0.8**	**0.8**	**1.0**	**0.8**	**1.0**	**5**
C12	**0.2**	**0.5**	**0.7**	**0.7**	**0.6**	**0.8**	**4**
C13	**0.8**	**1.0**	**0.8**	**1.0**	**1.0**	**1.0**	**6**
C14	**0.3**	**0.5**	**0.8**	**0.8**	**0.7**	**0.9**	**4**
C15	0.2	0.6	0.5	0.8	0.5	0.8	3
C16	**0.7**	**0.5**	**0.7**	**1.0**	**0.6**	**1.0**	**5**
C17	0.6	0.1	0.5	0.2	0.2	0.4	1
C18	0.4	0.3	0.8	0.9	0.5	1.0	3
C19	**0.7**	**0.9**	**1.0**	**1.0**	**0.9**	**1.0**	**6**
C20	0.2	0.2	0.5	0.5	0.5	0.8	1
C21	0.2	0.1	0.3	0.5	0.1	0.8	1
C22	**0.4**	**0.7**	**0.7**	**1.0**	**0.6**	**1.0**	**5**
C23	0.2	0.8	0.3	0.6	0.4	0.7	3
C24	0.2	0.3	0.5	0.7	0.2	0.8	2
C25	1.0	0.1	0.3	1.0	0.1	1.0	3

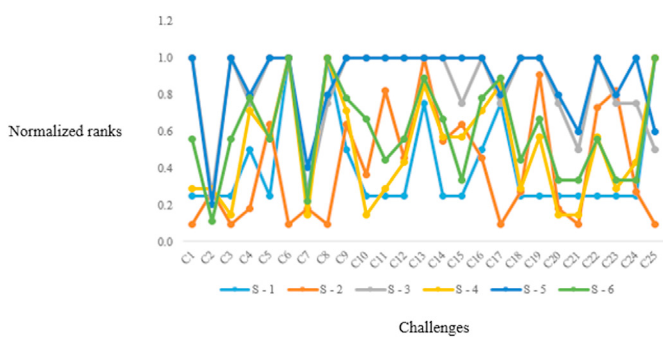

Fig. 4. Sensitivity analysis.

also be studied by the practitioners and management thus aiding in effective decision-making and devising policies that minimize the negative effects posed by the network of challenges.

- The study contributes by showcasing a relatively new method of severity assessment of the challenges using a new theory of multi-criteria decision-making. The technique can be used for the evaluation of the challenges with the help of the freely available software "jrank" (Błaszczyński et al., 2013). The given framework of decision-making can be made use of in grouping challenges of similar magnitude of severity as was shown in the decision rules in Table 4 and corrective actions can be taken for the group as a whole thereby saving time for the practitioners and streamlining the efforts towards a more targeted decision making.
- The study highlights the insurmountable challenge of huge initial investments and costs incurred to mobilize the IoT-enabled framework in construction firms. The recruitment of experts to train the employees and workers is seen as another big hurdle in the aforementioned objective. This is primarily attributed to the low education level of the workers employed at the Indian construction firms especially at the ground level. It is a challenge to educate and train them on sophisticated technology that requires a basic understanding of computer fundamentals and IT-related concepts that is found lacking in the workers employed at the lower levels. Proper maintenance of sensitive tools and equipment such as IoT devices is considered to be under serious threat due to the nature of the activities taking place at the construction sites.

Indian construction firms should incorporate the following strategies in order to raise awareness about the new technical revolution that can change the way the industry works forever in a good way. Consequently, providing an edge in the face of competition and increased productivity.

- There should be a detailed discussion with the board members, management, and workers about the understanding of the new concept of Industry 4.0. Before the management estimates the cost incurred it is of paramount importance to make every single person involved in the construction business acquainted with the emerging technology and the potential benefits it could provide.
- Authors suggest an integrated framework, in the beginning, phase of implementation of IoT-enabled operations, that includes three separate departments that comprise experts to firstly, familiarize the employees with the new technical concept and clarify the queries pertaining to the implementation and usage through dedicated induction and orientation programs. Secondly, providing hands-on experience to the users of the devices and equipment and educating them about the protocols and algorithms needed to be followed for the successful execution of the project. Lastly, a dedicated department of problem solvers that are experts in the field of IT and computers is to be available in case of any disruptions.
- Huge investments showed as the major threat in the implementation of Industry 4.0 in the Indian construction industry. Proper budgeting is needed before venturing into the implementation of the framework. Determination of timelines for the completion of the implementation process will result from

inefficient resource allocation in a pre-decided time frame in a cost-efficient manner.

- It was determined from the personal interaction with the management of the firm that the biggest and perhaps the most intractable hurdle standing in the way of adopting new technology is to reach a consensus from every level of the organizational hierarchy. More often than not, there are ideological differences between some segments of the firm regarding the inclusion of completely new technology. This can be checked by gaining a clear comprehension of the benefits offered by Industry 4.0 and the advantages it can offer by simplifying operations and also increasing the safety of the employees.

6. Conclusions

Based on the extant literature and intense discussions with the construction management and academicians, major impediments in the adoption of Industry 4.0 were identified, cross-verified, and ranked by experts from different disciplines that were either involved directly or implicitly with the construction business. The impact assessment of the challenges was carried out using the Dominance-based Rough set approach (DRSA) which is based on the Rough set theory.

Industry 4.0 is revolutionizing the face of the industrial sector in unbelievable ways. Yet due to the lack of sufficient background information and potential benefits offered by the adoption of this framework, Industry 4.0 is still considered an alien concept replete with unknown consequences. Particularly, in a developing country like India where sufficient awareness about smart technology and advanced automation methods is yet to be created in the industrial construction sector, it is a complicated and time-consuming process to instill confidence about the benefits Industry 4.0 would bring about thereby increasing the productivity of the firms. 25 key challenges were discovered in the adoption of Industry 4.0 in the Indian construction firms taking into account the inputs from the management, academicians, and IT professionals. The ranking using the Dominance-based Rough set approach provides a sound background to analyze the uncertainty and inconsistency in the evaluation of the severity degree of each challenge from all perspectives. The primary findings of the study point out the major threats or obstacles in the adoption of Industry 4.0 with the topmost ranks attributed to the most severe challenge followed by less severe ones. Sensitivity analysis conducted for the different combinations of the perspectives, however, revealed that all the challenges considered in the study need necessary attention at a different point in time of the implementation of the Industry 4.0 framework. It is, therefore, concluded that the challenges considered for the study do not exist independently of each other and as a result, should be analyzed and tackled together.

The current study focuses on identifying the barriers to the adoption of Industry 4.0 in the Indian construction sector.

The study suffers from several limitations and caveats as follows. A limited sample size of respondents impedes the generalizability of the results of the study. More decision-makers can be considered for the analysis from other backgrounds such as government, public, etc. to extend diversity to the analysis.

There can be a number of additional barriers to the adoption of the Industry 4.0 framework that has not been considered for the current work. It also depends on the Industry chosen for the study. Future work can focus on different industries and the inclusion of other barriers besides the ones already considered.

The study was limited to a small construction firm based in a small part of India. This can lead to problems in the generalization of the results for a similar industry but in a different location.

The preference information supplied by the decision-makers was used as the input to the decision-making process carried out using the Rough set theory. There exists the problem of subjectivity bias in the results that should be corrected by including more decision-makers as stated above.

Future studies can be targeted toward studying the barriers in a different industry. The perspectives considered for the analysis are from three domains i.e. Information Technology (IT), Academia and Management levels. Further perspectives can be included in the study from environmental and public domains to have a detailed understanding of the perception of the emerging technology and its adoption in the industrial setup. Comparative analysis should be considered with other statistical techniques to establish causality between the factors and the non-adoption of the framework. The identified barriers and challenges can work very differently or can be completely different for another country. Thus, further study can be taken to identify the validity of the barriers in a different population setting.

References

Abdul-Hamid, A. Q., Ali, M. H., Tseng, M. L., Lan, S., & Kumar, M. (2020). Impeding challenges on industry 4.0 in circular economy: Palm oil industry in Malaysia. *Computers & Operations Research, 123*, Article 105052.

Afolayan, A. O., & de la Harpe, A. C. (2020). The role of evaluation in SMMEs' strategic decision-making on new technology adoption. *Technology Analysis & Strategic Management, 32*(6), 697–710.

Ahmadi, M., Osman, M. H. M., & Aghdam, M. M. (2020). Integrated exploratory factor analysis and Data Envelopment Analysis to evaluate balanced ambidexterity fostering innovation in manufacturing SMEs. *Asia Pacific Management Review, 25*(3), 142–155.

Akanmu, A., & Anumba, C. J. (2015). Cyber-physical systems integration of building information models and the physical construction. *Engineering Construction and Architectural Management, 22*(5), 516–535.

Anakpo, G., & Kollamparambil, U. (2021). Effect of automation on unemployment: The case of Southern Africa. *Development Southern Africa*, 1–12.

Arpaci, I. (2019). A hybrid modeling approach for predicting the educational use of mobile cloud computing services in higher education. *Computers in Human Behavior, 90*, 181–187.

ASME. (2019). 6 paths to the automated construction site Accessed on 31st August 2021 https://www.asme.org/engineering-topics/articles/manufacturing-design/6-paths-automated-construction-site.

Bag, S., Gupta, S., & Kumar, S. (2021). Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *International Journal of Production Economics, 231*, Article 107844.

Bag, S., & Pretorius, J. H. C. (2022). Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework. *International Journal of Organizational Analysis, 30*(4), 864–898. https://doi.org/10.1108/IJOA-04-2020-2120.

Banmairuroy, W., Kritjaroen, T., & Homsombat, W. (2022). The effect of knowledge-oriented leadership and human resource development on sustainable competitive advantage through organizational innovation's component factors: Evidence from Thailand's new S-curve industries. *Asia Pacific Management Review, 27*(3), 200–209.

Błaszczynski, J., Greco, S., Matarazzo, B., Słowinski, R., & Szelag, M. (2013). jMAF-Dominance-based rough set data analysis framework. In *Rough sets and intelligent systems-professor zdzisław pawlak in memoriam* (pp. 185–209). Berlin, Heidelberg: Springer.

Blaszczynski, J., Roman, S., & Szeląg, M. (2011). Sequential covering rule induction algorithm for variable consistency rough set approaches. *Information Scientist, 181*, 987–1002.

Błaszczynski, J., Słowinski, R., & Szelag, M. (2009). *VC-DomLEM: Rule induction algorithm for variable consistency rough set approaches. Research Report RA-07/09*. Poznan University of Technology.

Boggia, A., Rocchi, L., Paolotti, L., Musotti, F., & Greco, S. (2014). Assessing rural sustainable development potentialities using a dominance-based rough set approach. *Journal of Environmental Management, 144*, 160–167.

Chauhan, C., Singh, A., & Luthra, S. (2021). Barriers to industry 4.0 adoption and its performance implications: An empirical investigation of emerging economy. *Journal of Cleaner Production, 285*, Article 124809.

Chavez, Z., Hauge, J. B., & Bellgran, M. (2021). Industry 4.0, transition or addition in SMEs? A systematic literature review on digitalization for deviation management. *International Journal of Advanced Manufacturing Technology*, 1–20.

Chen, C. H. (2022). The mediating effect of corporate culture on the relationship between business model innovation and corporate social responsibility: A perspective from small-and medium-sized enterprises. *Asia Pacific Management Review*. https://doi.org/10.1016/j.apmrv.2022.01.001

Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M., & Yin, B. (2018). Smart factory of industry 4.0: Key technologies, application case, and challenges. *IEEE Access, 6*, 6505–6519.

Cugno, M., Castagnoli, R., & Büchi, G. (2021). Openness to Industry 4.0 and performance: The impact of barriers and incentives. *Technological Forecasting and Social Change, 168*, Article 120756.

Dixit, A., Jakhar, S. K., & Kumar, P. (2022). Does lean and sustainable manufacturing lead to Industry 4.0 adoption: The mediating role of ambidextrous innovation capabilities. *Technological Forecasting and Social Change, 175*, Article 121328.

Dobni, C. B., Wilson, G. A., & Klassen, M. (2022). Business practices of highly innovative Japanese firms. *Asia Pacific Management Review, 27*(3), 155–162.

Financial express Accessed on 28th July 2021 https://www.financialexpress.com/industry/what-is-industry-4-0-why-it-offers-huge-opportunity-for-india/1452171/, (2019).

Forbes. (2019) Accessed on 28th July 2021 https://www.forbes.com/sites/bernardmarr/2016/04/05/why-everyone-must-get-ready-for-4th-industrial-revolution/#3942501d3f90.

Fortemps, P., Greco, S., & Słowinski, R. (2008). Multicriteria decision support using rules that represent rough-graded preference relations. *European Journal of Operational Research, 188*, 206–223.

Frustaci, M., Pace, P., Aloi, G., & Fortino, G. (2018). Evaluating critical security issues of the IoT world: Present and Future challenges. *IEEE Internet of Things Journal, 5*(4), 2483–2495.

Greco, S., Matarazzo, B., & Słowinski, R. (1999). Rough approximation of a preference relation by dominance relations. *European Journal of Operational Research, 117*, 63–83.

Greco, S., Matarazzo, B., & Slowinski, R. (1999). The use of rough sets and fuzzy sets in MCDM. In *Multicriteria decision making* (pp. 397–455). Boston, MA: Springer.

Greco, S., Matarazzo, B., & Słowinski, R. (2001). Rough sets theory for multi-criteria decision analysis. *European Journal of Operational Research, 129*, 1–47.

Greco, S., Matarazzo, B., & Słowiński, R. (2007). Dominance-based rough set approach as a proper way of handling graduality in rough set theory. In *Transactions on rough sets VII* (pp. 36–52). Berlin, Heidelberg: Springer.

Greco, S., Matarazzo, B., & Słowiński, R. (2008). Dominance-based rough set approach to interactive multiobjective optimization. In *Multiobjective optimization* (pp. 121–155). Berlin, Heidelberg: Springer.

Greco, S., Matarazzo, B., Slowinski, R., & Stefanowski, J. (2000). Variable consistency model of dominance-based rough sets approach. In *International conference on rough sets and current trends in computing* (pp. 170–181). Berlin, Heidelberg: Springer.

Greco, S., Słowinski, R., & Matarazzo, B. (2001b). An algorithm for induction of decision rules consistent with dominance principle. In W. Ziarko, & Y. Y. Yao (Eds.), *Rough sets and current trends in computing 2001, volume 2005 of lecture notes in artificial intelligence* (pp. 304–313). Berlin: Springer.

Hasan, A., Ahn, S., Rameezdeen, R., & Baroudi, B. (2019). Empirical study on implications of mobile ICT use for construction project management. *Journal of Management in Engineering, 35*(6), Article 04019029.

Hermann, M., Pentek, T., & Otto, B. (2016). Design principles for industrie 4.0 scenarios. In *2016 49th Hawaii international conference on system sciences (HICSS)* (pp. 3928–3937). IEEE.

Hofmann, E., & Rüsch, M. (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in Industry, 89*, 23–34.

Hsieh, Y. J., & Wu, Y. J. (2019). Entrepreneurship through the platform strategy in the digital era: Insights and research opportunities. *Computers in Human Behavior, 95*, 315–323.

Hwang, G., Lee, J., Park, J., & Chang, T. W. (2017). Developing performance measurement system for Internet of Things and smart factory environment. *International Journal of Production Research, 55*(9), 2590–2602.

Kalsoom, T., Ahmed, S., Rafi-ul-Shan, P. M., Azmat, M., Akhtar, P., Pervez, Z., Imran, M. A., & Ur-Rehman, M. (2021). Impact of IoT on manufacturing industry 4.0: A new triangular systematic review. *Sustainability, 13*(22), Article 12506.

Kamble, S. S., Gunasekaran, A., Ghadge, A., & Raut, R. (2020). A performance measurement system for industry 4.0 enabled smart manufacturing system in SMMEs-A review and empirical investigation. *International Journal of Production Economics, 229*, Article 107853.

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018). Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. *Computers in Industry, 101*, 107–119.

Kergroach, S. (2017). Industry 4.0: New challenges and opportunities for the labour market. *Форсайт, 11*(4), 6–8.

Khanzode, A. G., Sarma, P. R., Mangla, S. K., & Yuan, H. (2021). Modeling the industry 4.0 adoption for sustainable production in micro, small & medium enterprises. *Journal of Cleaner Production, 279*, Article 123489.

Kim, D., Park, K., Park, Y., & Ahn, J. H. (2019). Willingness to provide personal information: Perspective of privacy calculus in IoT services. *Computers in Human Behavior, 92*, 273–281.

Kim, T. H., Ramos, C., & Mohammed, S. (2017). Smart city and IoT. *Future Generation Computer Systems, 76*, 159–162.

Kirimtat, A., Krejcar, O., Kertesz, A., & Tasgetiren, M. F. (2020). Future trends and current state of smart city concepts: A survey. *IEEE Access, 8*, 86448–86467.

Kokina, J., & Blanchette, S. (2019). Early evidence of digital labor in accounting: Innovation with robotic process automation. *International Journal of Accounting Information Systems, 35*, Article 100431.

Kolberg, D., & Zühlke, D. (2015). Lean automation enabled by industry 4.0 technologies. *IFAC-PapersOnLine*, 1870–1875.

Kumar, C. (2016). Industry 4.0: IISc building India's 1st smart factory in Bengaluru Accessed 25th August 2021 https://timesofindia.indiatimes.com/city/bengaluru/Industry-4-0-IISc-building-Indias-1st-smart-factory-in-Bengaluru/articleshow/53441112.cms.

Kumar, P., Bhamu, J., & Sangwan, K. S. (2021). Analysis of barriers to Industry 4.0 adoption in manufacturing organizations: An ISM approach. *Procedia CIRP, 98*, 85–90.

Kumar, S., Raut, R. D., Nayal, K., Kraus, S., Yadav, V. S., & Narkhede, B. E. (2021). To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP. *Journal of Cleaner Production, 293*, Article 126023.

Kusunoki, Y., Błaszczyński, J., Inuiguchi, M., & Słowiński, R. (2021). Empirical risk minimization for dominance-based rough set approaches. *Information Sciences, 567*, 395–417.

Laufs, J., Borrion, H., & Bradford, B. (2020). Security and the smart city: A systematic review. *Sustainable Cities and Society, 55*, Article 102023.

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing letters, 3*, 18–23.

Leitão, P., Colombo, A. W., & Karnouskos, S. (2016). Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges. *Computers in Industry, 81*, 11–25.

Lekan, A., Clinton, A., & James, O. (2021). The disruptive adaptations of construction 4.0 and industry 4.0 as a pathway to a sustainable innovation and inclusive industrial technological development. *Buildings, 11*(3), 1–28.

Lin, Y. C., & Cheung, W. F. (2020). Developing WSN/BIM-Based environmental monitoring management system for parking garages in smart cities. *Journal of Management in Engineering, 36*(3), Article 04020012.

Liou, J. J., & Tzeng, G. H. (2010). A dominance-based rough set approach to customer behavior in the airline market. *Information Sciences, 180*(11), 2230–2238.

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & Industrial Engineering, 113*, 144–159.

van Lopik, K., Sinclair, M., Sharpe, R., Conway, P., & West, A. (2020). Developing augmented reality capabilities for industry 4.0 small enterprises: Lessons learnt from a content authoring case study. *Computers in Industry, 117*, Article 103208.

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration, 6*, 1–10.

Majumdar, A., Garg, H., & Jain, R. (2021). Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework. *Computers in Industry, 125*, Article 103372.

Make in India. (2019a). Construction Accessed on 30th August 2021 http://www.makeinindia.com/sector/construction.

Make in India. (2019b). Towards smart manufacturing industry 4.0 and India Accessed on 25th August 2021 http://www.makeinindia.com/article/-/v/towards-smart-manufacturing-industry-4-0-and-india.

Masood, T., & Egger, J. (2019). Augmented reality in support of Industry 4.0—implementation challenges and success factors. *Robotics and Computer-Integrated Manufacturing, 58*, 181–195.

Masood, T., & Sonntag, P. (2020). Industry 4.0: Adoption challenges and benefits for SMEs. *Computers in Industry, 121*, Article 103261.

Mastos, T. D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., & Tzovaras, D. (2020). Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution. *Journal of Cleaner Production, 269*, Article 122377.

Mckinsey & company. (2019) Accessed on 20th August 2021 https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/The%20Internet%20of%20Things%20The%20value%20of%20digitizing%20the%20physical%20world/Unlocking_the_potential_of_the_Internet_of_Things_Executive_summary.ashx.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *Cirp Annals, 65*(2), 621–641.

Moradi, E., Jafari, S. M., Doorbash, Z. M., & Mirzaei, A. (2021). Impact of organizational inertia on business model innovation, open innovation and corporate performance. *Asia Pacific Management Review, 26*(4), 171–179.

Mosterman, P. J., & Zander, J. (2016). Industry 4.0 as a cyber-physical system study. *Software and Systems Modeling, 15*(1), 17–29.

Mrugalska, B., & Wyrwicka, M. K. (2017). Towards lean production in industry 4.0. *Procedia Engineering, 182*, 466–473.

Müller, J. M., Kiel, D., & Voigt, K. I. (2018). What drives the implementation of industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability, 10*(1), 1–24.

Narayanamurthy, G., & Tortorella, G. (2021). Impact of COVID-19 outbreak on employee performance–moderating role of industry 4.0 base technologies. *International Journal of Production Economics, 234*, Article 108075.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W. D., & Rillie, I. (2020). Industry 4.0 deployment in the construction industry: A bibliometric literature review and UK-based case study. *Smart and Sustainable Built Environment, 10*(4), 557–580.

Nimawat, D., & Gidwani, B. D. (2022). An overview of industry 4.0 in manufacturing industries. *International Journal of Industrial and Systems Engineering, 40*(4), 415–454.

NIST. (2019). Product definitions for smart manufacturing Accessed on 20th August 2021 https://www.nist.gov/programs-projects/product-definitions-smart-manufacturing.

Ozkan-Ozen, Y. D., & Kazancoglu, Y. (2021). Analysing workforce development challenges in the Industry 4.0. *International Journal of Manpower, 43*(2), 310–333.

Pawlak, Z. (1996). Institute of theoretical and applied informatics. In *Soft computing in intelligent systems and information processing: Proceedings of the 1996 asian fuzzy systems symposium* (p. 1). Kenting, Taiwan, ROC: Institute of Electrical & Electronics Engineers (IEEE). December 11-14, 1996.

Pourmehdi, M., Paydar, M. M., Ghadimi, P., & Azadnia, A. H. (2022). Analysis and evaluation of challenges in the integration of Industry 4.0 and sustainable steel reverse logistics network. *Computers & Industrial Engineering, 163*, Article 107808.

Preuveneers, D., & Ilie-Zudor, E. (2017). The intelligent industry of the future: A survey on emerging trends, research challenges and opportunities in industry 4.0. *Journal of Ambient Intelligence and Smart Environments, 9*(3), 287–298.

Qi, B., Razkenari, M., Costin, A., Kibert, C., & Fu, M. (2021). A systematic review of emerging technologies in industrialized construction. *Journal of Building Engineering, 39*, Article 102265.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A. B. L., & Rajak, S. (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *International Journal of Production Economics, 224*, Article 107546.

Rana, N. P., Dwivedi, Y. K., & Hughes, D. L. (2021). Analysis of challenges for blockchain adoption within the Indian public sector: An interpretive structural modelling approach. *Information Technology & People, 35*(2), 548–576.

Rojko, A. (2017). Industry 4.0 concept: Background and overview. *International Journal of Interactive Mobile Technologies (iJIM), 11*(5), 77–90.

Roma, R., Ottomano Palmisano, G., & De Boni, A. (2020). Insects as novel food: A consumer attitude analysis through the dominance-based rough set approach. *Foods, 9*(4), 1–19.

Saka, A. B., & Chan, D. W. (2020). Profound barriers to building information modelling (BIM) adoption in construction small and medium-sized enterprises (SMEs): An interpretive structural modelling approach. *Construction Innovation, 20*(2), 261–284.

Setyaningsih, S., Kelle, P., & Maretan, A. S. (2020). Driver and barrier factors of industry 4.0 implementation for small and medium-sized enterprises: An overview. *Economic and Social Development: Book of Proceedings*, 343–354.

Sharma, M., Kamble, S., Mani, V., Sehrawat, R., Belhadi, A., & Sharma, V. (2021). Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies. *Journal of Cleaner Production, 281*, Article 125013.

Singh, A., & Misra, S. C. (2020). A Dominance based Rough Set analysis for investigating employee perception of safety at workplace and safety compliance. *Safety Science, 127*, Article 104702.

Smith, D. (2019). The robots are coming: Probing the impact of automation on construction and society. *Construction Research and Innovation, 10*(1), 2–6.

Stojkoska, B. L. R., & Trivodaliev, K. V. (2017). A review of Internet of Things for smart home: Challenges and solutions. *Journal of Cleaner Production, 140*, 1454–1464.

Sulistyo, H., & Siyamtinah. (2016). Innovation capability of SMEs through entrepreneurship, marketing capability, relational capital and empowerment. *Asia Pacific Management Review, 21*(4), 196–203.

Szeląg, M., Słowiński, R., Greco, S., Błaszczyński, J., & Wilk, S. (2010). jRank-ranking using dominance-based rough set approach. *Newsletter of the European Working Group "Multiple Criteria Decision Aiding, 3*(22), 13–15.

Tortorella, G. L., & Fettermann, D. (2018). Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International Journal of Production Research, 56*(8), 2975–2987.

Tsai, W. L. (2021). Constructing assessment indicators for enterprises employing cloud IaaS. *Asia Pacific Management Review, 26*(1), 23–29.

Vijayakumar, V., Malathi, D., Subramaniyaswamy, V., Saravanan, P., & Logesh, R. (2019). Fog computing-based intelligent healthcare system for the detection and prevention of mosquito-borne diseases. *Computers in Human Behavior, 100*, 275–285.

Wagire, A. A., Joshi, R., Rathore, A. P. S., & Jain, R. (2021). Development of maturity model for assessing the implementation of industry 4.0: Learning from theory and practice. *Production Planning & Control, 32*(8), 603–622.

Yang, X., Yang, J., Wu, C., & Yu, D. (2008). Dominance-based rough set approach and knowledge reductions in incomplete ordered information system. *Information Sciences, 178*(4), 1219–1234.

Yaqoob, I., Ahmed, E., Hashem, I. A. T., Ahmed, A. I. A., Gani, A., Imran, M., & Guizani, M. (2017). Internet of things architecture: Recent advances, taxonomy, requirements, and open challenges. *IEEE Wireless Communications, 24*(3), 10–16.

Yeo, C. J., Yu, J. H., & Kang, Y. (2020). Quantifying the effectiveness of IoT technologies for accident prevention. *Journal of Management in Engineering, 36*(5), Article 04020054.

Yigitcanlar, T., Kankanamge, N., & Vella, K. (2021). How are smart city concepts and technologies perceived and utilized? A systematic geo-twitter analysis of smart cities in Australia. *Journal of Urban Technology, 28*(1–2), 135–154.

Yoon, C., Lim, D., & Park, C. (2020). Factors affecting adoption of smart farms: The case of Korea. *Computers in Human Behavior, 108*, Article 106309.

Zabidin, N. S., Belayutham, S., & Ibrahim, C. K. I. C. (2020). A bibliometric and scientometric mapping of Industry 4.0 in construction. *Journal of Information Technology in Construction, 25*, 287–307.

Zhai, L. Y., Khoo, L. P., & Zhong, Z. W. (2009). A dominance-based rough set approach to Kansei Engineering in product development. *Expert Systems with Applications, 36*(1), 393–402.

Dr. Arpit is Lecturer of Operations and Decision sciences at Jindal Global Business School (JGBS) at O. P. Jindal Global University (Institute of Eminence), India. He has rich industrial experience in the Investment banking and Private Equity Research sectors. He holds a Ph.D. in Industrial and Management Engineering from the Indian Institute of Technology (IIT) Kanpur Uttar Pradesh and an M.Tech in Operations Research (Gold Medalist) from National Institute of Technology (NIT) Durgapur, West Bengal and a B.Tech. in Electrical and Electronics Engineering (First Class) from Dr. K.N.Modi Foundation, Ghaziabad, Uttar Pradesh, India. Arpit's research interest is in the areas of Decision making under uncertainty, Big data Analytics, Statistical applications in business problems, and adoption of new technologies in the business domain. His work on these research areas has been published in multiple international peer reviewed (ABDC/ABS ranked) journals and top international conferences on Advanced computing and intelligent engineering including Safety Science (Elsevier), International Journal of Quality and Reliability Management (Emerald), and Behaviour and Information Technology (Taylor & Francis).

Vimal Kumar is an Assistant Professor at Chaoyang University of Technology, Taichung, Taiwan (R.O.C.) in the Department of Information Management. He completed his Postdoctoral Research at Chaoyang University of Technology, Taichung, Taiwan (R.O.C.) in the Department of Business Administration in the domain of Technological Innovation and Patent Analysis. He has served as an Assistant Professor under TEQIP III, an initiative of MHRD, Govt. of India at AEC Guwahati in the Department of Industrial and Production Engineering. Prior to joining AEC, he served as Assistant Professor at MANIT, Bhopal in the Department of Management Studies and also served as Visiting Faculty at IMT Nagpur. He obtained his PhD in the domain of TQM and Manufacturing Strategy in the year 2017 and Masters in Supply Chain Management from the Department of Industrial & Management Engineering, IIT Kanpur in the year 2012. He graduated (B.Tech) in Manufacturing Technology from JSS Academy of Technical Education Noida, in the year 2010. He has published thirty-two articles in reputable international journals and presented twenty-four papers at international conferences. His research paper entitled ***"Time Table Scheduling for Educational Sector on an E-Governance Platform: A Solution from an Analytics Company"*** has been **selected for best paper award** in the International Conference on Industrial Engineering and Operations Management (IEOM) held in Bandung, Indonesia, March 6–8, 2018. He was also invited to serve as session chair of session on ***"Energy Related Awareness"*** held on 19th September 2018 at iCAST 2018, **IEEE** International Conference on Awareness Science and Technology and ***"Lean Six Sigma"*** at the International Conference on Industrial Engineering & Operations Management (IEOM-2018) at Bandung, Indonesia and ***"Quality Control & Management"*** at the International Conference on Industrial Engineering & Operations Management (IEOM-2016) at Kuala Lumpur, Malaysia. He is a contributing author in journals including *Supply Chain Management: An International Journal, BSE, TFSC, JKM, CSREM, IJOA, IJPPM, IJQRM, IJPMB, IJPQM, IJBIS, AJOR, The TQM Journal, and Benchmarking: An International Journal*, etc. and also a guest reviewer of a reputable journal like *IJQRM, TQM & Business Excellence, The TQM Journal, Benchmarking: An International Journal, Journal of Asia Business Studies, and JSIT.* He is the corresponding author and can be contacted at vimaljss91@gmail.com or vimalkr@gm.cyut.edu.tw

Pratima Verma is currently working as an Assistant Professor in the Department of Strategic Management at Indian Institute of Management and associated with Chaoyang University of Technology, Taichung, Taiwan. She has worked as an Assistant Professor in Strategic Management area at Indian Institute of Management (IIM) Bodh Gaya, India. Prior to joining IIM, she was Postdoctoral Fellow in the Department of Management Studies at IIT Madras, India. She obtained her PhD from IIT Kanpur where she worked in the domain of Strategic Management and Horizontal Strategy in the Department of Industrial & Management Engineering, in the year 2017. She received her MBA in Finance and Human Resource Management from BBDNITM, Uttar Pradesh Technical University- Lucknow, India in the year 2011. She completed her graduation (B.Tech) in Information Technology in the year 2009 from BBNITM, Lucknow. She has one year of experience in teaching. She also awarded JRF/SRF in the area of human resource management. She has published ten articles in reputable international journals and presented fourteen papers at international conferences. Her research paper entitled "***Time Table Scheduling for Educational Sector on an E-Governance Platform: A Solution from an Analytics Company***" has been selected for best paper award in the International Conference on Industrial Engineering and Operations Management (IEOM) held in Bandung, Indonesia, March 6–8, 2018. She was invited to serve as session chair for Human Factors and Ergonomics Track at the International Conference on Industrial Engineering & Operations Management at Kuala Lumpur, Malaysia. She is a contributing author in International journals including *Supply Chain Management: An International Journal, CLSCN, IJOA, JEEE, IJPPM, IJQRM, The TQM Journal, IJPMB, IJISE, IJBIS, and Benchmarking: An International Journal*, etc.

Jayakrishna is an Associate professor in the School of Mechanical Engineering at the Vellore Institute of Technology University, India. Dr. Jayakrishna's research is focused on the design and management of manufacturing systems and supply chains to enhance efficiency, productivity and sustainability performance. More recent research is in the area of developing tools and techniques to enable value creation through sustainable manufacturing, including methods to facilitate more sustainable product design for closed-loop material flow in industrial symbiotic setup, and developing sustainable products using hybrid bio composites. He has mentored doctoral students, graduate and undergraduate students (2 Ph.D, 2 M.Tech Thesis and 31 B.Tech Thesis)

which have so far led to 68 journal publications in leading SCI/ SCOPUS Indexed journals, 28 book chapters, and 91 refereed conference proceedings, 7 books in CRC/ Springer Series. Dr. Jayakrishna's team has received numerous awards in recognition for the quality of the work that has been produced. He teaches undergraduate and graduate courses in the manufacturing and industrial systems area and his initiatives to improve teaching effectiveness have been recognized through national awards. He has also been awarded Global Engineering Education Award from Industrial Engineering and Operations Management (IEOM) Society International, U.S.A. in 2021, Institution of Engineers (India)-Young Engineer Award in 2019 and Distinguished Researcher Award in the field of Sustainable Systems Engineering in 2019 by International Institute of Organized Research, Best Faculty Researcher Award for the year(s) 2016–2021 consecutively. Coordinator -Circular Economy Club, VIT University, Academic Editor – Mathematical Problems in Engineering, Wiley-Hindawi Publications and Editorial Board Member – Journal of Operational Research for Engineering Management Studies (JOREMS), Area Editor – Operations Management Research, Associate Editor – Circular Economy, Frontiers in Sustainability, Book Series Editor - Industrial Engineering, Systems, and Management, CRC Press.