STUDY OF SELECT ISSUES OF INDUSTRY 4.0 AND CIRCULAR ECONOMY

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CERTIFICATE

This is to certify that the thesis entitled **"Study of select issues of Industry 4.0 and Circular Economy"** being submitted by **ABHISHEK SAHU** to the Delhi Technological University, Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him. He has worked under our guidance and supervision and fulfilled the requirements for the submission of this thesis, which has reached the requisite standard.

The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

Manufacturing industry offers one of the greatest opportunities for India, not only to spur economic growth but also for job creation and driving innovation. It has transformed the landscape from mass production to customized production. With digital transformation being a crucial component in achieving an advantage in this fiercely competitive industry. To achieve this target, “Make in India”, “Digital India” and “Samarth Udyog Bharat 4.0” must be integrated with the principles of Industry 4.0 and make the transition to smart manufacturing. The Government of India is gradually progressing on the road to Industry 4.0 through the Government of India’s initiatives like the National Manufacturing Policy, which aims to increase the share of manufacturing in GDP to 25 percent by 2025. Further, the transformation of traditional manufacturing and production practices due to emerging Industry 4.0 technologies allows substantial improvements in business operations, processes, productivity, quality, and manufacturing networked systems. According to the report given by waste management society of India, the adoption of a circular economy in India may result in yearly benefits of $624 billion by 2050 and a 44% reduction in greenhouse gas emissions. The circular economy plays a vital character in preserving the environmental condition and creating an ecological balance to encourage the recycling of waste products. Therefore, the research work aims to consider the execution of Industry 4.0 and circular economy across India’s manufacturing industry. A review of the existing literature reveals that studies on Industry 4.0 and the circular economy are still in a nascent stage of development and major challenges pertaining to adoption and implementation, circularity decisions, legal informatics implementation, and triple bottom line performance measurement systems are under-represented in existing research and need to be investigated further. Therefore, this thesis provides qualitative as well as quantitative methods to fill the research gaps by using survey methods, case studies, statistical models and conceptual frameworks associated with select issues from the viewpoint of the Indian manufacturing

industry.

A survey of Indian manufacturing industry was carried out to explore the various factors related to Industry 4.0 and Circular Economy. Based on the hypotheses development, a questionnaire was developed and distributed through email and Google form links. Further, a questionnaire was divided into eight sections that cover all the important factors corresponding with Industry 4.0 and circular economy implementation in Indian manufacturing industry. A total of 370 forms were distributed to the Indian manufacturing industry and overall 120 responses from manufacturing industry were found relevant to descriptive analysis and hypotheses testing. The questionnaire's validity and reliability were tested extensively by statistical analysis. The hypotheses based on various factors were developed and tested through structural equation modelling methodology.

It was found from the survey and hypotheses testing that circularity decisions are the significant factors which affect the triple bottom line performance of the Industry 4.0 and circular economy.

Furthermore, the present research established a performance measure framework which is based on triple bottom line perspectives of sustainability with the help of a value engineering approach. The research work aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. Further, these findings may be useful for industrialists and researchers in implementing value engineering and circular economy effectively in their practices.

The research work further identified and prioritized key challenges of Industry 4.0 and circular economy implementation through ANP Fuzzy-TOPSIS methodology in an Indian manufacturing organization.

A model for the circularity index was developed through graph theory and matrix approach, which calculates the maximum circularity index and percentage of circularity.

The research work contributed to the very limited studies available on circularity decisions by establishing a method for selecting the optimum circularity index through graph theory and matrix approach. The research work also incorporates the sustainability concepts into the Industry 4.0 and circular economy and contributes to the very few studies available on integration of sustainability with Industry 4.0 and circular economy from the perspective of Indian manufacturing organizations. The present study investigates the following important contribution to the research work.

- An extensive review of Industry 4.0 and circular economy have been carried out that focused on theoretical aspects, conceptual frameworks, maturity models and other building blocks. Based on the detailed literature analysis while considering both qualitative and quantitative aspects, the research work has identified the research gaps and formulated the research objectives of the study that integrated with various issues and challenges on which the study was conducted.
- The research motivated the Indian manufacturing industry and made a major contribution to the very few articles that are available corresponding to Industry 4.0 and circular economy implementation from the Indian manufacturing organization.
- A detailed questionnaire was established and a survey of the Indian manufacturing organization was carried out. The results of descriptive analysis and hypotheses of the survey may be useful for industrialists and managers to have a better insight into the Indian manufacturing industry. It may also establish the foundation for further investigation of the manufacturing industry.
- To perform descriptive analysis and hypotheses testing, hypotheses were developed associated with drivers, barriers, enablers, key challenges, circularity decisions, and value engineering benefits and their association with the performance of Industry 4.0 and circular

economy. The researchers and industrialists may employ the findings of the hypotheses for identifying and analyzing these factors for improving Industry 4.0 and circular economy performance.

- A case illustration of a barrel manufacturing industry has been discussed and supported that very limited case studies are available for Indian manufacturing organizations integrated to value engineering and circular economy.
- A framework integrating the concept of value engineering into circular economy is established to evaluate the triple bottom line performance of the circular economy. The framework provides that the very few studies are available on performance measuring systems of product development and circular economy, especially from triple bottom line perspectives.
- The research work identified and prioritized the major issues and challenges for the Indian manufacturing Industry using ANP Fuzzy-TOPSIS methodology. Very limited studies were available on key challenges for the Indian manufacturing organization. The findings of the research may be useful for researchers and industrialists in decision-making to ensure the easy execution of Industry 4.0 to develop a circular economy.
- A circularity decision framework was established with the help of identifying the several circularity attributes and evaluating the optimum circularity alternative through graph theory and matrix approach. The results of the study may improve the circularity performance of Industry 4.0 and circular economy. In addition, the circularity framework may also be useful for industrialists and managers in circularity decisions and measurement of the circularity index while allocating with the quality and quantity of return products.
- A conceptual framework has been established to facilitate the integration of Industry 4.0 into the field of legal informatics. It has been concluded that the implementation of Industry 4.0 technologies may help legal informatics systems achieve their goal. It may also support

lawmakers to align jurisprudence by enabling advanced information technology to improve the existing legal justice system.

TABLE OF CONTENTS

Contents **Page No.**

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CE	Circular Economy
SCM	Supply Chain Management
BDA	Big Data Analytics
IoT	Internet of Things
CPSs	Cyber-Physical-Systems
VE	Value Engineering
CBM	Circular Business Model
TBL	Triple Bottom Line
ANP	Analytic Network Process
AHP	Analytic Hierarchy Process
MCDM	Multi Criteria Decision Making Process
GTMA	Graph Theory and Matrix Approach
PLSPM	Partial Least Square Path Modelling
AVE	Average Variance Extracted
CR	Composite Reliability
RFID	Radio Frequency Identification
SEM	Structural Equation Modelling
SMEs	Small and Medium Enterprises
PLSPM	Partial Least Squares Path Modelling
CB	Covariance Based
LISREL	Linear Structural Relations
AMOS	Analysis of Moment Structure

Chapter 1

Introduction

1.1 Background

In the present scenario, circular economy (CE) has gained a lot of attention because it replaces the end-of-life philosophy and works towards cleaner production and sustainable development. It develops a cost-effective product with reduced power consumption, CO_2 emission and minimum wastage of raw material. Conversely, Industry 4.0 is combined with advanced technologies which help the organizations in flexibility and agile manufacturing operations. CE implementation from the Industry 4.0 perspective may reduce the requirement for virgin resources, high waste generation, huge CO_2 emissions and ecological degradation caused by resource extraction. Further, managing circularity in the supply chain is becoming more challenging with a large number of returned products. To achieve the sustainable development goals, it is essential to convert the linear economy into a circular business model, which can be denoted as a CE. It is a contemporary method that encourages conserving natural resources and minimizing wasteful practices. It points out on maximizing the resource's circularity within production systems. It is based on the concept of a closed-loop supply chain that highlights restorative and regenerative characteristics. The main target of CE implementation is to reduce dependency on the conventional source of energy, prevent the usage of contaminated compounds, CO_2 emissions, and energy consumption and recommend stakeholders in the development of environmental sustainability. In case of CE, the coordination between material and data flow plays an essential role in strengthening circular strategies, especially the collection of waste product data, types of waste, amount of waste and the required technologies to facilitate or manage these data (Nascimento et al., 2019). To develop a circular supply chain, both manufacturers and consumers should be well aware of the quality, quantity and optimum use of raw materials from waste, including their ecological advantages. However, due to insufficient technological development and unavailability of essential data, manufacturers might not know how to collect information on continuing deteriorating resources and recycled products. Similarly, consumers might hesitate or rigid the quality of alternatives such as secondary products compared to primary products and abstain from purchasing sustainably. To overcome this challenge, Industry 4.0 technologies can transform CE by providing real-time status about continuing deteriorating resources or waste products, streamlining industrial processes and identifying failure and error in between processes. Consequently, the probability of breakdown can be minimized (Kouhizadeh et al., 2020). Industry 4.0 enablers encouraged CE by maximizing the circularity of resources, managing the supply chain practices, improving the reverse logistic procedure and avoiding ecological damage affected by resource extraction. It also allows keeping the information together with the material in the cycle and makes it conceivable to utilize waste as a resource.

In the current manufacturing environment of CE, industries need to use the emerging technology of Industry 4.0 for product monitoring, component failure and error and reverse logistic processes, which may help waste recovery and maintain product value chains. Industry 4.0 technologies have potential to transform circular business models in the various phases of the supply chain. The prime objective of Industry 4.0 execution is to provide an advanced level of functional accuracy and flexibility. It can also deliver the information related to failure and errors, product quality, resource utilization, unconventional waste and condition of used products by using end-to-end visibility. Furthermore, Industry 4.0 based technologies improve the decision-making, inventory control, network monitoring, reduce the breakdowns and waste generation caused by resource extraction, which can help the longer life of products and facilities. The integration of Industry 4.0 technologies into CE has been utilized in a number of studies. Dev et al. (2020) utilized the ReSOLVE model and integrated Industry 4.0 and CE approaches in the viewpoint of reverse logistic processes that can be implemented by adopting data-sharing technology. Moreover, Zhou et al. (2020) implemented Industry 4.0 and CE approaches in the manufacturing organization and identified economic drivers using a dynamic spatial model. Chauhan et al. (2019) established the SAP-LAP structure and recognized that top managers play an important character in the integration of Industry 4.0 and CE. Garcia-Muiña et al. (2018) developed a circularity model and integrated sustainable development principles into Industry 4.0 and CE.

This research work has explored the various issues and challenges of Industry 4.0 and CE in the Indian manufacturing industry. The Indian manufacturing industry has been selected because of its higher growth and size. This research work addresses the factors, particularly adoption and implementation of Industry 4.0 and CE, circularity decisions, value engineering, and performance evaluation system through statistical analysis, model development and case studies.

Furthermore, the implementation of legal informatics using Industry 4.0 may strengthen the legal justice system by enabling decision-making provisions, real-time tracking, data security, and cost-effective determinations. Consequently, this research work proposes to evaluate the adoption arrangements of Industry 4.0 technology by government agencies and legislative bodies.

1.2 Industry 4.0

In the beginning of first industrial revolution (1760-1830), the manufacturing facilities were mainly dependent on water and steam-powered engines. The second industrial revolution (1870-1914) focused on an assembly line and mass production using automation and electricity. Furthermore, the third industrial revolution began in the 1950s and was marked by an increase in production through the transition from analog to digital technology (Ghobakhloo, 2018). As per Lee et al. (2015), the development of ICT's in the production system led to the fourth industrial revolution. In contrast to previous revolutions, the fourth industrial revolution leads to the beginning of production through a cyber-physical system, collaborative entities, learning machines, and autonomous robots. In fact, it is also considered a symbol of horizontal and vertical integration that increases connectivity between the different systems and sub-systems of industry. The design principles of Industry 4.0, including decentralization, interconnection, real-time monitoring, data security, and technical assistance are identified by Hermann et al. (2016). Later, Liao et al. (2017) defined Industry 4.0 based on real-time data transfer among different systems and sub-systems that increase digitalization in the entire supply chain. Zhong et al. (2017) identified five fundamental technologies of Industry 4.0, such as Cyber-Physical-Systems, Internet of Things, Big Data, Cloud Computing, and Cyber-Security. Most of these technologies are centered on the development of smart products and smart manufacturing processes by incorporating modern ICT's. Figure 1.1 represents the key technologies of Industry 4.0. Several studies have addressed these important technologies of Industry 4.0.

i. Internet of Things

It is a network of devices developed with an embedded system and connected through the internet. In addition, it can transfer massive amounts of data over a standardized interface without human intervention required (Lomotey et al., 2018).

ii. Cloud computing

It is an internet-based architecture that employs remote servers to store, and process data to advance service attributes, consistency and offer cost-effective determinations (Sharma et al., 2019; Sahu et al., 2022). The wide application of cloud computing has many benefits in the distribution of legal services (Sharma, 2016). Legal service providers can adopt the cloud-based software model to earn profit. It offers numerous advantages over the traditional bespoke service model by storing and handling useful information, routing tasks, and customer-based service cost-effectively.

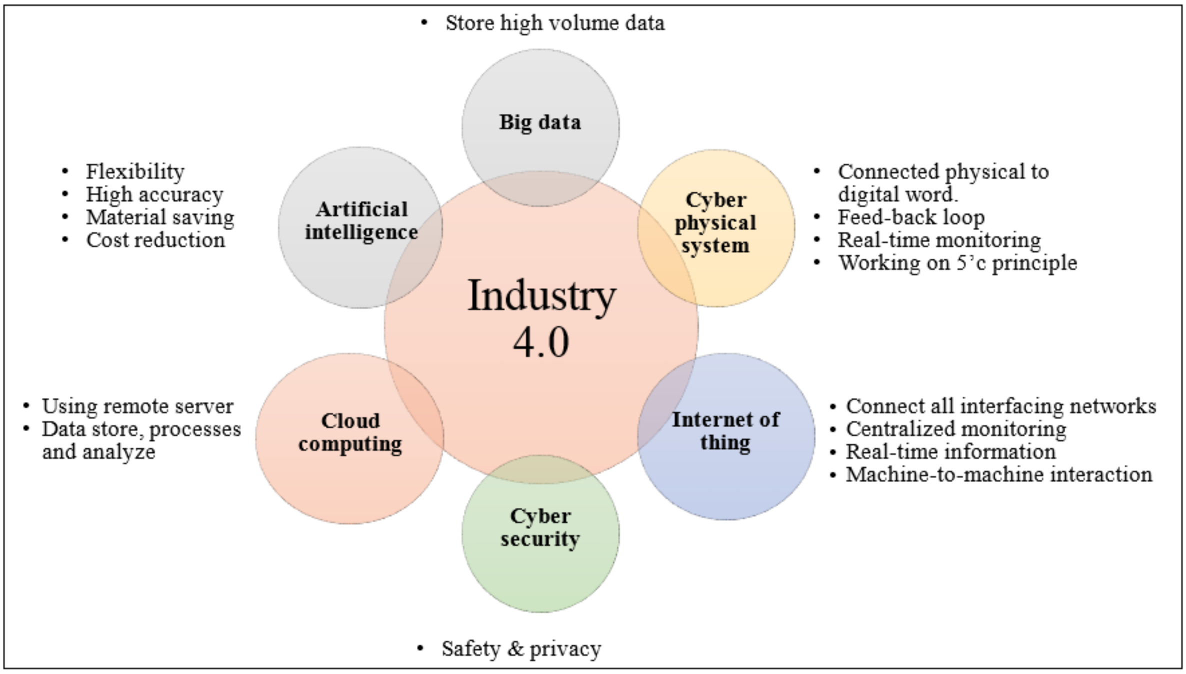

Figure 1.1 Key technologies of Industry 4.0

iii. Big Data Analytics

This technology is useful in making critical decisions for the organization (Sharma et al. 2014). It can develop the most profitable pricing strategies. Big data science is helpful in handling a large volume, variety and velocity of data. Manual data analysis could be effective when the total amount of data is minimal. However, it is ineffective when dealing with Big Data (Sivarajah et al., 2017). The ongoing fastest growing of data has required the development of new and effective information retrieval and data mining approaches, while raw Big Data is not directly useful in traditional database management systems.

iv. Cyber-Physical Systems (CPSs)

CPSs is a computer-based transformative mechanism that is controlled and monitored by computational algorithms (Kumar et al., 2020a; Oztemel and Gursev, 2020). CPSs can be constructed by the following 5'c principle: connection, conversion, cognition, configuration, and cyber (Tao et al., 2019).

- Connection – It incorporates a local agent as well as a communication protocol for sending information from a remote server to a central server.

- Conversion - In a business environment, data can originate from a variety of sources, including controllers, sensors, industrial systems and maintenance records. These data characterize the condition of the systems, which will be further converted into meaningful information for a practical purpose.
- Cyber - It is also termed as cyber level because the information is used to construct cyber avatars for physical machines and establish an extensive database for each machine system.
- Cognition – At this level, the machine uses the remote monitoring system to detect the potential failure and alert its deterioration before failure.
- Configuration – The configuration level works as a feedback loop between cyberspace and physical space, and it assists as a supervisory control to allow machines to self-configure and self-adaptive.

v. Cybersecurity

Cybersecurity is a new term for information security, and it even extended to an industrial environment. It specifically relies on detecting, protecting, and responding to cyber-attacks (Sahu et al., 2022). The cybersecurity technique is affected by various types of threats, such as phishing attacks, integrity attacks, adversarial assaults, zero-day exploits and malware attacks (Agrawal et al., 2022).

1.3 Circular Economy

The concept of CE offers a sustainable solution over the evolution from a linear economy (take-make-use-dispose) to a circular approach (take-make-use-recycle) by offering waste into the recycled product (Geissdoerfer et al., 2017; Kalmykova et al., 2018; Garcia-Muiña et al., 2018; Chauhan et al., 2019). In other words, CE is an umbrella term that provides a solution to minimize the use of virgin material and resource consumption (Murray et al., 2017; Moraga et al., 2019; Bag et al., 2020a). As reported by Ellen MacArthur Foundation (2017), it proposes the restorative and regenerative perspective of the products and materials to minimize the design of waste and generate the highest utility and value in all circumstances. Furthermore, Kirchherr et al. (2017) and Kirchherr and Piscicelli (2019) explained CE as a commercial value that changes the ‘end-of-life’ perception by reducing, recycling, and remanufacturing the resources to maintain sustainable development. The CE works on three principles, including conservation of natural assets, accumulative the circularity of resources, and reducing the adverse effects on the system and surrounding (Ellen MacArthur Foundation, 2013). As reported by Su et al. (2013) all these principles of CE required to advance technology and development for modernizing existing facilities and machinery.

1.4 Industry 4.0 and Circular Economy Implementation in India

CE approach has been implemented in India for a long period. “Olx”, in which dealers assist customers in reselling their used or refurbished products such as furniture, mobile phones, home appliances and automobiles. In retail, “Cashify” give sell old or used mobile phones under the "Phone Purana Hai" instant cash offer. Typically, these items are used or refurbished in local regions and usually sold in the secondary markets. Another aspect of CE is soft drinks producers, namely Pepsi and Limca have a very successful CE approach of frequently reusing (refilling) glass bottles. Likewise, petroleum companies provide cooking gas to customers by replenishing LPG cylinders. In rural India, the interchange of new steel cooking utensils for used clothing is also relatively common. These are a few examples of where Indian organizations have successfully implemented CE. The CE strategies can also have the potential to reduce carbon emissions, minimize environmental pollution, and avoid biodiversity and habitat loss caused by resource extraction (Kristoffersen et al., 2020). According to Kalmykova et al. (2018), CE implementation can save European Union corporations up to € 600 billion through eco-design, waste reduction, and reuse culture while lowering GHG emissions. Furthermore, additional actions are required to increase production efficiency by 30% by 2030, which could raise GDP by about 1% and generate 2 million new employments. However, CE activities are limited in developing economies such as India. Additionally, the academic research reflects the limited amount of studies performed. This could be due to inadequate legislation, a lack of involvement of top management, an attitude of workers, and company policies towards CE implementation. Lack of knowledge about the latest technologies can also be one of the leading aspects that can discourage stakeholders from participating. The majority of CE work is spread across a variety of industries in the Indian environment. Industry 4.0 technologies from a CE perspective, may provide automation, real-time monitoring, data exchange, optimal resource utilization, and a circular business model that handles environmental and managerial disruptions caused by the pandemic (Rauch *et al*., 2020; Centobelli *et al.*, 2020). Rajput et al. (2020) reported that Industry 4.0 technologies are the backbone of CE implementation and can optimize resource circularity within operational structures of production and consumption. Previous research has concentrated on the phenomenon of the fundamental design philosophies and scientific developments to accelerate the comprehension of the Industry 4.0 architecture. Subsequently, Industry 4.0 is a contemporary development of advanced technology, and the knowledge gap between Industry 4.0 and CE is partially explored. De Jesus and Mendonça (2018) identified economic, social and environmental barriers and drivers of the Indian manufacturing industry. Kumar et al. (2020a) identified fifteen challenges in the execution of Industry 4.0 and CE in Indian Small and Medium-Sized Enterprises (SMEs). Further, Kumar et al. (2021) identified barriers in the period of Industry 4.0 and CE to improve the sustainability of a supply chain. Gölzer and Zhou (2015) found data and cybersecurity, smart device development, big data and analytics, and ecological side-effects as the major challenges of Industry 4.0 in the Indian organization. Furthermore, Thames and Schaefer et al. (2017) addressed the complexity of integrating digital and manufacturing technologies, which also leads to the current challenges of the present manufacturing organization. Additionally, Tseng et al. (2018) identified that Industry 4.0 technologies could be employed to empower the CE by reducing the resource consumption and waste generated by industrial activities. Yadav et al. (2020) proposed the hybrid best-worst technique to evaluate the weight of the sustainable supply chain barriers from the viewpoint of Industry 4.0 and CE. Rajput and Singh (2020) established a mixed-integer linear programming technique for Industry 4.0 to implement CE by minimizing the overall cost and power consumption of the machine. While there are several studies but no particular industry has been investigated in depth from the viewpoints of Industry 4.0 and CE.

1.5 Indian Manufacturing Industry

Manufacturing industry is developing significantly with the adoption of modern technology and product innovation in an international market. The demand for manufacturing products especially consumer manufacturing is growing substantially due to digitalization and information technology developments worldwide. The Indian manufacturing industry is one of the fastest-growing industries in the world. Under the Production Linked Incentive (PLI scheme, the government plans to create global manufacturing champions across 13 sectors and has allocated Rs. 1.97 lakh crore (US$ 27.13 billion) over the next five years (starting FY22). The manufacturing industry of India has capability to reach US$ 1 trillion by 2025. The implementation of the Goods and Services Tax (GST) will make India a common market with a GDP of US$ 2.5 trillion along with a population of 1.32 billion people, which will be a big draw for investors. With an impetus on developing industrial corridors and smart cities, the Government aims to ensure the holistic development of the nation. Further, According to management consulting company McKinsey & Company, Indian organization may boost their operational profit by 40 per cent and lower the anticipated capital expenditure by 10 per cent merely by implementing Industries 4.0. Figure 1.2 shows the metrics of expected demand and production. The variation between supply and demand could be viewed as manufacturing potential and subsequently potential for activities associated with Industry 4.0 and CE. Digital India, Make-In-India, and Udyog Bharat 4.0 programme by the Government of India propose a significant amount of contribution to the growth of manufacturing organizations in India. “Make in India” has made significant advancements in 27 different industries. These also include strategic sectors of service and manufacturing industries as well. The “Make in India” initiative strengthens domestic manufacturing, forming resilient supply chains, making Indian industries more competitive and boosting the export potential. The "Make in India" campaign has also drawn the attention of international firms that are now looking to establish manufacturing facilities in India to provide to both domestic and international markets. The government has developed embedded systems technology centers, expanded liberalization, and lowered rates to promote foreign direct investment into the sector.

According to the Economic Report of India 2017-18, the country's manufacturing sector has been on the rise due to the government's encouraging initiatives like Make in India, which have increased its contribution to GDP to as high as 18 percent. The traditional "take, make, and dispose of" economic strategy underpins India's manufacturing growth challenges with the country's capacity to deliver and replenish its limited resources. India will need about 15 billion tonnes of resources by 2030 and just over 25 billion tonnes by 2050 if its economy keeps growing at its current rate. The essential need to decouple economic growth from resources is better served by adopting a CE strategy, as material needs currently exceed supply. The contribution of manufacturing industry to the CO2 or greenhouse gas emissions has increased from 15% in 1995 to 23% in 2015. These greenhouse gas emissions, however, originated mostly in the production of materials that are utilized to construct buildings and vehicles.

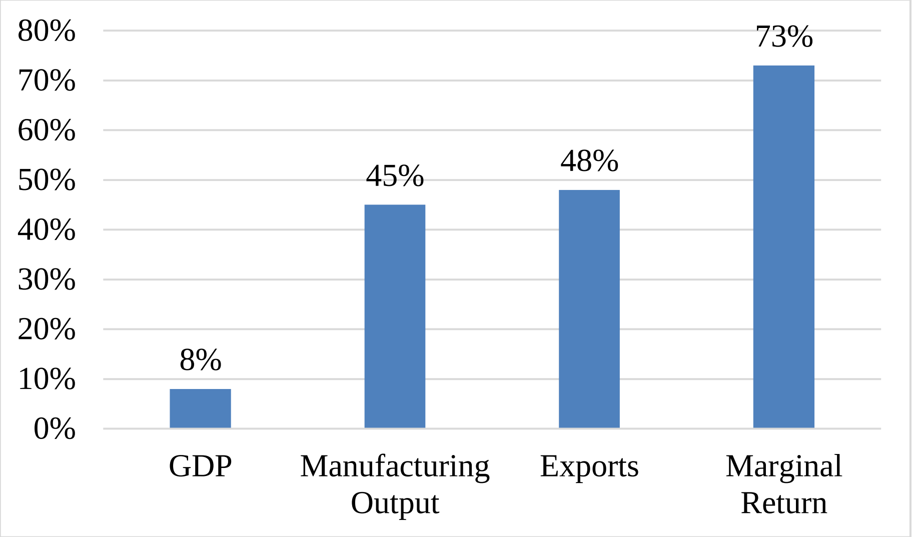

Figure 1.2 Role of manufacturing industry in Indian economy and social development

The transition to a CE could result in an additional US$ 4.5 trillion in global economic output by 2030. Furthermore, in contrast to the current growth environment, India's CE development route might produce an annual worth of US$ 218 billion by 2030 and US$ 624 billion by 2050. The implementation of a CE in India would require an allowing environment that encourages the identification and adoption of new business models. India's Ministry of Environment, Forest, and Climate Change (MoEFCC) shows a critical function in advancing the CE throughout the country's most important economic spheres. As a result, industries that generate a considerable amount of waste (such as the plastics and electronics industries) are required by law to obtain the EPR authorization from a regulating body like CPCB. Circular jobs and sustainable economic growth are two outcomes that could result from India's shift to a CE. A research by the World Economic Forum estimates a potential economic effect of $15 trillion and the creation of up to 50 million jobs.

1.6 Issues in the implementation of Industry 4.0 and Circular Economy

In the adoption of Industry 4.0 and CE, various issues come across the production process. Based on the extensive literature review, the major issues associated with Industry 4.0 and CE have been identified, classified and carried out in the following subsections.

1.6.1 Legal and ethical issues

According to Eltantawy et al. (2009), ethical responsibilities in the supply chain are to manage the optimum flow of high-quality and value-for-money products or services in a reasonable manner. The legal and ethical issues are presented in the supply chain investigation often related to working conditions, environmental exploitation, and corruption (Ferrell et al., 2013). Further, excessive industrialization directly affects working conditions and the diversity of human resources and their rights, health, safety, etc (Luthra and Mangla, 2018). The workplace safety condition, including the use of protecting goggles, the availability of medical facilities, and human rights violations, creates a hazardous effect on workers' life (Kamble et al., 2018b). Moreover, the issue is related to corruption from suppliers that can maintain their revenue by selling unsafe products to the customer and avoiding safety standards (Herndon, 2005). To manage Industry 4.0, the ethical responsibilities in the supply chain require proper controlling and monitoring between all suppliers and distributors (Gonzalez-Padron, 2016). Additionally, using modern technologies of Industry 4.0, the risks of mismanaging the confidential information, copy-write issues, and data transparency through cyber-crime are always there.

1.6.2 Operational issues

Identifying operational aspects of Industry 4.0 and CE in manufacturing industries is crucial. Many operational issues come across the current organization, including unskilled workforce, forecast demand of the product and advancement of new technology (Tseng et al., 2018). Every year, the development of advanced technologies, including IoT, Big Data, and CPSs, certainly get manufacturers overwhelmed, whereas digitalization of the manufacturing process leads to sustainability. These developments encompass considerable challenges at the organization and the administrative level (Lu, 2017). The current operational issues that have been identified in manufacturing industries using such technologies are:

- Lack of information, unskilled workforce, and high implementation cost.
- Lack of expertise to lead digitalization initiatives.
- Excessive digitalization of processes creates security and privacy issues.
- It is challenging to develop recycling or remanufacturing capabilities in an organization.
- IT snags, which would be the reason for the high production cost.
- Loss of employment due to automation, especially in SMEs sectors.
- Excessive digitalization may lead to contributed lower health standards and the worker's safety (Luthra and Mangla, 2018; Kurt, 2019).

1.6.3 Demographic issues

Artificial intelligence, big data, IoT, and other technological development may dominate the Industry 4.0. However, the people who are working in the organization and leading them are always beating hearts. It is a reality of every organization that new technologies and business policies cannot proceed without judgment of human decision-making capability (Al-Fuqaha et al., 2015). The main issue that comes across the current organization is the demographic changes. It affects both the industry environment and productivity.

According to Wolf et al. (2018), increasing the average age of the workers is the leading cause of the demographic issues. Another critical issue is the supporting technologies and assistance system for elderly workers (Machado et al., 2020). In this situation, elderly workers are usually not much compatible with the upcoming technologies, which affects the production process for the design and development of an innovative product. In addition, there is a larger proportion of elderly workers in the organizations. Consequently, it may be challenging to deliver them with internal training and skill development programs for the purpose of acquiring modern technology (Kelloway and Barling, 2000; Mital and Pennathur, 2004). As the average age of the workforce increases, physical, psychological, mental, and emotional capabilities affect the worker's strength and attention. Consequently, it affects the overall output of the manufacturing process (Köchling, 2003; Thun et al., 2007; Badri et al., 2018).

In the working environment of Industry 4.0, demographic issues do not create many disadvantages in the production system. Sometimes, it also increases the performance and optimization skills of the workers. The transition of physical work into automated, high IT-competence ability to exchange with machines, networked systems and interdisciplinary thinking will be beneficial for product development. Subsequently, the collaboration of technology with experience and problem-solving ability of elderly workers is much better compared to their young colleagues (Ghobakhloo, 2020).

1.7 Motivation of the Research Work

The execution of Industry 4.0 and CE are at the earlier stage of development and there is a significant opportunity for future work scope. Existing studies demonstrate that research is scattered and diverse among industries and some of the factors have received relatively less attention in earlier studies. This research work is intended to identify, investigate, and explore these factors in the Indian context. The Indian manufacturing sector was considered for the study due to its rapid expansion, massive size, and strong sustainable development rules and regulations in place or planned for implementation by the Indian government between 2016 and 2021. The present research work addresses the various factors associated with the adoption and implementation of Industry 4.0 and CE, circularity decisions and performance evaluation of Industry 4.0 and CE with the help of descriptive analysis and hypotheses testing, case study, and development of conceptual frameworks and models. The state-of-art investigation on Industry 4.0 and CE factors and recent advancements in the Indian industry, specifically manufacturing industry encouraged research in this range. The major findings of the study are summarized as follows:

- The literature study reveals that both Industry 4.0 and CE are still in the nascent stage of development and very limited studies have been performed in developing countries like India (Discussed in Chapter 2).

- The study is diversified across the sectors, and no single sector has been explored and analyzed extensively.
- The Government of India has taken several initiatives such as “Make in India”, “Digital India”, “Udyog Bharat 4.0”, “Sustainable Development Rules and Regulations-2011, 2016”, and various government policies offer great opportunities for Industry 4.0 and CE in the Indian manufacturing industry.
- India is dependent heavily on imports of raw materials and finished products. Investment in India's industrial sector may be encouraged through the Government of India initiatives. CE has considerable ability for development due to the developing manufacturing industry and the introduction of rules for managing waste disposal.
- It was observed that select issues and current challenges, including adoption and implementation, performance measures and circularity decisions of Industry and CE are not completely addressed and require further research. These factors provide a great opportunity for the study, especially in the context of the Indian manufacturing industry. In chapter 2, a review of the significant literature is discussed in detail on these factors.

1.8 Research Objectives

The research gaps identified above are addressed through the following research objectives. These research objectives collectively establish this thesis and are explained in the subsequent chapters.

- To study and analyze the manufacturing industry from Industry 4.0 and circular economy perspectives.
- To develop the model for the integration of Industry 4.0 and circular economy.

- To identify challenges in the adoption and implementation of Industry 4.0 for manufacturing industry.
- To develop the framework for measuring the circularity of the manufacturing industry.

1.9 Findings of the study

The significant contributions of the research work are enumerated as follows.

- A comprehensive literature review of Industry 4.0 and Circular Economy have been carried out that establishes a sufficient basis for other contemporary researchers and developed the transition framework.
- Survey method was used to analyze the recent developments in the Industry 4.0 and Circular Economy of Indian manufacturing industry through descriptive analysis and hypothesis testing.
- A framework incorporating the concept of triple bottom line into Circular Economy is developed for the evaluation of performance of Circular Economy. The model is based on the value engineering approach and fulfill the product as well as sustainable development objectives.
- An integrated framework of GTMA and sustainability proposed for evaluating the strategy based circularity decisions in Industry 4.0 and Circular Economy. “Percentage of Circularity” and “Circularity Index” for various strategy based alternatives were determined and decision may be taken based on these indices.
- A framework for the identification of key challenges for Industry 4.0 and Circular Economy of Indian manufacturing industry was developed by using ANP Fuzzy-TOPSIS methodology.
- The framework of legal informatics was developed using Industry 4.0 based technology.

10. Organization of the Thesis

This thesis is organized into nine chapters and the flow of these chapters are shown in Figure 1.3. A brief description of the research work carried out in each chapter is enlightened below.

Chapter 1- "Introduction", provides the background and introduction of the study. It includes an overview of Industry 4.0 and circular economy and its conversion from traditional manufacturing to automate and data-driven smart manufacturing. The chapter also explains application of Industry 4.0 and circular economy from the perspective of Indian manufacturing industry. This chapter further explains the importance as well as the motivation for the study. The organization of the thesis and a summary of each chapter is also explained comprehensively.

Chapter 2- "Literature Review", an extensive literature review is discussed and explored to establish a detailed summary of the existing and contemporary research in Industry 4.0 and circular economy. Definitions and new developments in the area of Industry 4.0 and circular economy are discussed in this chapter. The comprehensive literature review also focuses on the various factors of research work, including adoption and implementation, such as barriers, drivers, enablers and challenges of the Industry 4.0 and circular economy. This chapter also discusses the circularity decisions, value engineering implementation and performance measurement framework of Industry 4.0 and circular economy. A research gaps analysis was carried out based on the extensive literature review, and research gaps were identified. Based on a research gap analysis, research objectives were formulated. The review of the literature also facilitated in establishment the future scope of the study.

Chapter 3- "Research Methodology", conceptual structure for the study is explained with the help of a research flow diagram. This chapter also explains the several methodologies employed for the research work, including the survey method using structural equation modelling, case study using a value engineering approach, and other conceptual frameworks. The ANP Fuzzy-TOPSIS approach is employed to identify and prioritize key challenges, and finally, Graph Theory and Matrix Approach is employed for evaluating the circularity decisions of Industry 4.0 and circular economy. The chapter also provides a brief introduction to the methodologiesand the rationale for the selection of these methodologies.

Chapter 4- "Descriptive Analysis and Hypotheses Testing", developments of hypotheses and procedures are explained thoroughly. This chapter explains the hypotheses formulation on the basis of the systematic literature review and detailed discussion with industry experts. The steps involved in developing and distributing a questionnaire, collecting and analyzing responses, respondent's profile along with conducting validity and reliability tests are explained and covered in detail. A structural equation modelling method is utilized to perform a survey using the partial least square path modelling technique.

Chapter 5- "Case Study", triple bottom line performance of the manufacturing organization is evaluated by using case study method. The value engineering approach is utilized in a case study of ABC barrel manufacturing organization with a circular economy perspective. The study aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emission and minimum wastage of raw material. These findings may be useful for researchers and industrialists in implementing value engineering and circular economy effectively.

Chapter 6- "Identification and Prioritization of Implementation Factors for Industry 4.0 and Circular Economy" a thorough study of various factors such as drivers, barriers, enablers, key issues and current challenges and their ordered implementation for successful Industry 4.0 and Circular Economy implementation is discussed. This chapter starts with an introduction and provides information on the selection of key challenges by using a literature review and detailed discussions with the industry experts. The proposed ANP Fuzzy-TOPSIS model is utilized for prioritizing the various criteria. The findings of the research work may be useful for developing Industry 4.0 and CE in their organization after incorporating above-mentioned challenges and achieving a higher level of effectiveness and efficiency.

Chapter 7- "Development of a framework for the legal issues in the implementation of Industry 4.0", conceptual framework is developed that incorporates Industry 4.0 with legal informatics. This chapter begins with an introduction and provides information on Industry 4.0 and legal informatics by using a literature review. It is observed that the execution of these emerging technologies will be beneficial in fulfilling the objectives of legal informatics. It may also support lawmakers to align jurisprudence through advanced information and technology to improve and transform the existing legal justice system.

Chapter 8- "Development of performance framework for measuring the circularity of Industry 4.0 and Circular Economy", this chapter emphasizes on the establishment of the framework for the circularity decisions in Industry 4.0 and circular economy. The research establishes a model for circularity decisions in Industry 4.0 and circular economy, while implementing Industry 4.0 and circular economy practices partly or fully. Based on an extensive literature review and industry experts, the research work identified and prioritized the circularity alternatives to improve the triple bottom line aspect of sustainability. The findings of the research may be beneficial to academicians and researchers in strategic decision-making for achieving circularity decisions in their organizations.

Chapter 9- "Conclusions and future directions" provides a discussion and future scope of the research work. The chapter also presents the major contributions and key research findings made from the thesis. Further, the implications of research for academicians, industrialists and researchers are summarized along with the limitations and future research directions in the field of Industry 4.0 and circular economy.

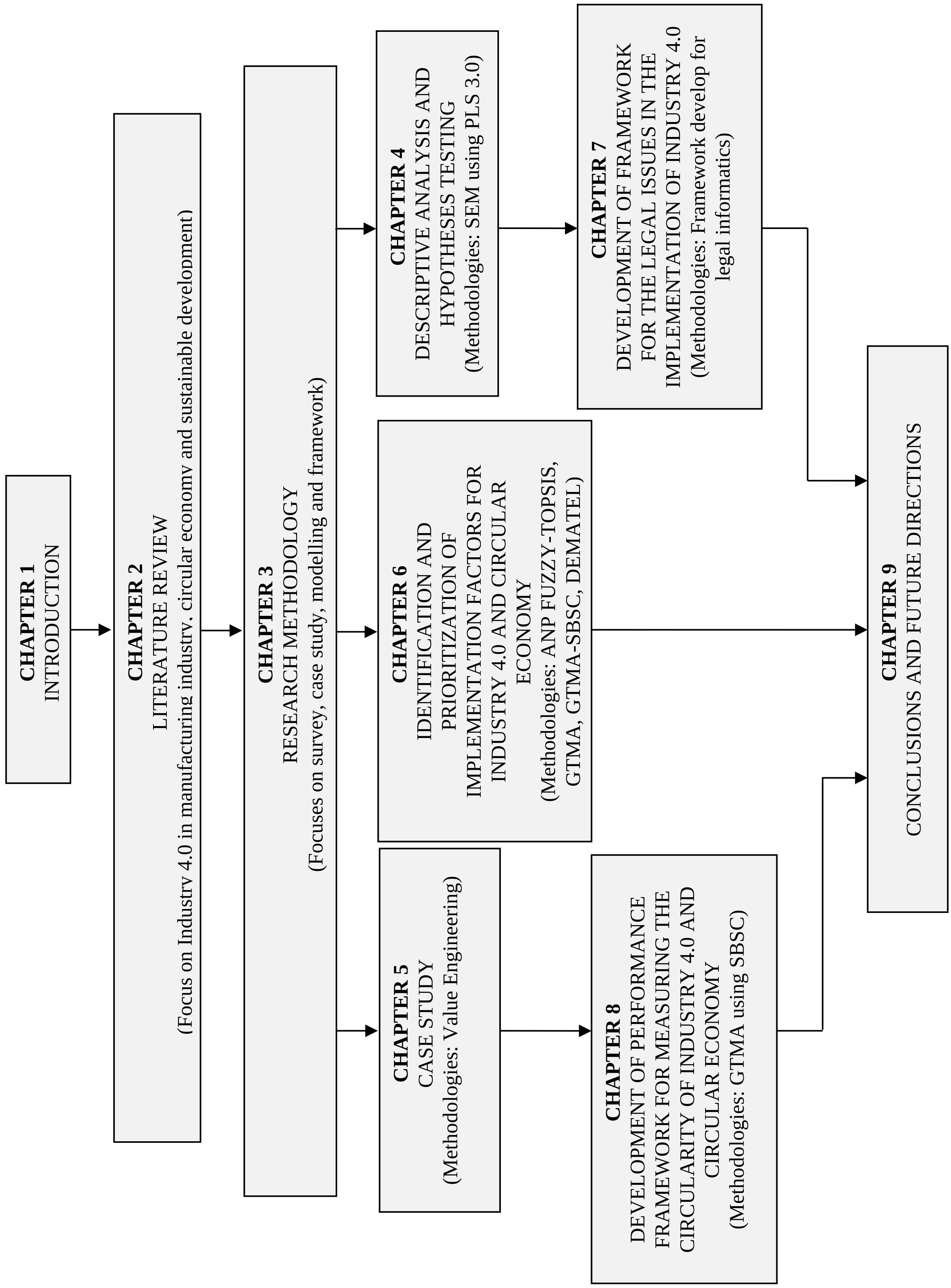

Figure 1.3 Organization of the thesis

Chapter 2

Literature Review

2.1 Introduction

The chapter provides an extensive literature review on Industry 4.0 and CE. The literature review is structured on the basis of different perspectives of Industry 4.0 and CE. Additionally, the chapter also provides important definitions, frameworks, and select issues of Industry 4.0 and CE with the help of a comprehensive review methodology and investigates the gaps in state-of-the-art research in Industry 4.0 and CE. An extensive literature review is conducted to investigate the existing studies associated with Industry 4.0 and CE. In this chapter, developments of definitions of Industry 4.0 and CE implemented by the researchers and practitioners broadly are reviewed along with key features of Industry 4.0 and CE. Detailed classifications of Industry 4.0 and CE processes are also enumerated in this chapter. The Industry 4.0 and CE approaches are explained on the basis of the most widespread attributes utilized by researchers in earlier studies. The Industry 4.0 and CE frameworks are also categorized in several ways in the literature. The study investigated the reduce, recycle, reuse, and secondary marketplace networks to have a greater understanding of Industry 4.0 and CE practices. A comprehensive methodology proposed by Mayring (2003) was implemented for the literature review. The literature review methodology includes data collection, descriptive analysis, category selection and content evaluation. The study analyzed various factors on the basis of previous literature reviews and research gaps in the literature discussed through existing studies. The study further investigates the various factors, such as adoption and implementation, circularity decisions, and performance evaluation of Industry 4.0 and CE. A comprehensive analysis of these factors was considered, and research gaps in the literature

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were identified. A higher level of inter-rater reliability was achieved through the literature review, and the validity was rigorously tested. The following sections present the key definitions of CE and Industry 4.0 in detail.

2.2 Definitions of Circular Economy

The model of CE offers a sustainable solution through the evolution from a linear economy (take-make-use-dispose) to a circular approach (take-make-use-recycle) by offering waste into the recycled product (Geissdoerfer et al., 2017). In other words, CE is an umbrella term that provides a solution to minimize the use of virgin material and resource consumption (Bag et al., 2022). According to Ellen MacArthur Foundation (2017), it proposes the restorative and regenerative perspective of the products and materials to reduce the design of waste and generate the highest utility and value in all circumstances. Furthermore, Kirchherr et al. (2017) explain CE as an economic structure that replaces 'end-of-life' conception by reducing, recycling, and remanufacturing the resources to maintain sustainable development. The CE works on three principles, including the conservation of natural assets, increasing the circularity of resources, and reducing the adverse effects on the systems and surroundings. According to Su et al. (2013), all these principles of CE are required to advance technology and development for updating existing facilities and machinery. Some of the CE definitions are represented in Table 2.1.

Table 2.1 Definitions of Circular Economy

Authors	**Definition**
Ellen MacArthur Foundation (2013)	It is "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, and eliminates the use of toxic chemicals".

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Kalmykova et al. (2018)	It proposes "the restorative and regenerative perspective of the products and materials to reduce the design out waste".
European Commission (2015)	An economic system "where the value of resources and funds are preserved in the economy for as long as feasible and waste generation is reduced.
Sauvé et al. (2016)	It indicates the "production and consumption of goods through closed-loop material flows that internalize environmental externalities linked to virgin resource extraction and the generation of waste (including pollution)''.
EEA (2016)	A circular economy provides opportunities to create well-being, growth and jobs while reducing environmental pressures. The concept can, in principle, be applied to all kinds of natural resources, including biotic and abiotic materials, water and land.

2.3 Definitions of Industry 4.0

In the beginning of the first industrial revolution (1760-1830), the manufacturing facilities were mainly dependent on water and steam-powered engines. The second industrial revolution (1870-1914) focused on an assembly line and mass production using automation and electricity. Furthermore, the third industrial revolution began in the 1950s and was marked by an increase in production through the transition from analog to digital technology (Ghobakhloo, 2018). As per Lee et al. (2015), the development of ICT's in the production system led to the fourth industrial revolution. Unlike the revolutions that preceded it, the fourth industrial revolution leads to the beginning of production through a cyber-physical system, collaborative entities, learning machines, and autonomous robots. In fact, it is also considered a symbol of horizontal and vertical integration that increases connectivity between the different systems and sub-systems of industry. The design principles of Industry 4.0, such as decentralization, interconnection, real-time data transparency, and technical assistance are identified by Hermann et al. (2016). Later, Liao (2017) defined Industry 4.0 based on real-time data transfer among different systems and sub-systems that increase digitalization in the entire supply chain. Zhong

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et al. (2017) identified five key technologies of Industry 4.0, such as Cyber-Physical-Systems (CPSs), Internet of Things (IoT), Big Data, Cloud Computing, and Cyber-Security. Most of these technologies are centered on the development of smart products and smart manufacturing processes by incorporating modern ICT's. Some of the Industry 4.0 definitions are summarized in Table 2.2.

Table 2.2 Definitions of Industry 4.0

Authors	**Definition**
MacDougall (2014)	• Refers to the technological evolution from embedded systems to cyber-physical systems. • It connects embedded system production technologies and smart production processes to pave the way to a new technological age which will radically transform the industry, production value chains and business models.
Koch et al. (2014)	• It stands for the fourth industrial revolution and is best understood as a new level of organization. • It controls the entire value chain of the life cycle of products, and it is geared towards increasingly individualized customer requirements.
Deloitte (2015)	• The term Industry 4.0 refers to a further development stage in the organization and management of the entire value chain process involved in the manufacturing industry.
Geissbauer et al. (2016)	• Industry 4.0 - the fourth industrial revolution, focuses on the end-to-end digitization of all physical assets and integration into digital eco-systems with value chain partners.
Pfohl et al. (2015)	• Industry 4.0 is the sum of all disruptive innovations derived and implemented in a value chain to address the trends of digitalization, atomization, transparency, mobility, modularization, and network collaboration and socializing of products and processes.

The current status of the work on CE in the field of Industry 4.0 is presented in Table 2.3. It was found that most of the researchers used Industry 4.0 elements and tried to correlate them

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with the existing models. Furthermore, a limited number of developing countries have taken preliminary initiatives toward Industry 4.0 and CE implementation.

Table 2.3 Current status of circular economy in the context of Industry 4.0

Authors	**Country**	**Method/Model**	**Analysis type**	**Contribution**
Rajput and Singh (2022)	India	Mixed Integer Linear Programming	Quantitative	Developed MILP model of Industry 4.0 for the integrated circular-reverse logistic network.
Ozkan-Ozen et al. (2020)	Turkey	Fuzzy-ANP	Quantitative	Prioritized CE barriers in the perspective of Industry 3.5/4.0.
Dev et al. (2020)	India	ReSOLVE model	Quantitative	Integrated Industry 4.0 technologies and RL in CE perspectives.
Rajput and Singh (2020)	India	Mixed-Integer Linear Programming (MILP)	Quantitative	Minimize the total cost and energy consumption of machines by employing Industry 4.0 technologies to achieve CE and cleaner production.
Zhou et al. (2020)	China	Dynamic spatial model	Quantitative	Identified economic driving forces using Industry 4.0 and CE.
Abdul-Hamid et al. (2020)	Malaysia	Fuzzy Delphi Method	Qualitative	Identified key challenges of Industry 4.0 and CE in the palm oil industry
Rajput and Singh (2019a)	India	DEMATEL approach	Quantitative	Identified significant enablers to connect Industry 4.0 and CE.
Chauhan et al. (2019)	India	SAP-LAP framework	Qualitative	Identified top managers and technologies like IoT, and CPSs that played an important role while integrating Industry 4.0 and CE.

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Kuo et al. (2019)	Taiwan	Simulation model	Comparative	Cross-nation analysis for industrial revitalization through Industry 4.0.
Nascimento et al. (2019)	Brazil	Circular business model	Qualitative	Explored Industry 4.0 technologies linked with CE for reuse of electronic waste.
De Sousa Jabbour et al. (2018)	France	ReSOLVE model	Qualitative	Developed ReSOLVE framework for Industry 4.0.
Tseng et al. (2018)	China	Big data analytics	Qualitative	Suggested the evolvement of cross-industrial networks in the area of CE and Industry 4.0.
Okorie et al. (2018)	United Kingdom	Data-driven approach	Qualitative	Identified circular approaches towards Industry 4.0.
Garcia-Muiña et al. (2018)	Spain and Italy	Circular business model	Qualitative	Integrated sustainability into Industry 4.0 and CE and developed a new CBM.

2.4 Literature Review Methodologies

According to Webster and Watson (2002), a review of the existing relevant literature is an important aspect of every academic article. An effective examination establishes a solid basis for knowledge advancement. It aids concept development, identifies areas where more study is needed and plugs gaps where there is already a lot of research. Further, the research methodology employed in this study incorporates both quantitative and qualitative methods. The first step of research methodology considers the important assumptions, facts, theories, and frameworks. On the basis of this dual methodological alignment, the study was organized by utilizing four methodological steps given by Kitchenham (2004), such as data extraction, descriptive analysis, category selection, and content evaluation.

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2.4.1 Data collection

According to Saunders et al. (2009), two research approaches were identified for the data extraction, i.e. deductive and inductive. The deductive approach considers the development of theories and hypotheses and designing of the test strategy to measure the hypotheses, whereas the inductive approach considers the data extraction and development theories according to the result of data analysis. The present study incorporates both approaches of research methodology. Further, mixed-method research has been used that considered both qualitative and quantitative data extraction methods and analysis procedures.

A two-step methodology was adopted for the extraction of data. According to Tranfield et al. (2003) and Petersen et al. (2015), the data extraction should include the following information such as article title, author name, country and year of publication details. During the first step, a pair of keywords “Industry 4.0” and “Circular economy” were used in the title, abstract, and country to search published articles from 2000 to 2023. These articles were collected through various databases such as Scopus (www.scopus.com), Web of Science (mjl.clarivate.com), ProQuest (www.proquest.com) and Google Scholar search engine (www.scholar.google.com)with English language journals only. Further, these articles correspond to a leading publishers such as Elsevier (www.sciencedirect.com), Springer (www.springerlink.com), and Emerald (www.emeraldinsight.com) etc. These databases were selected for the review as these include an exhaustive list of journals relevant to this study. Following the criteria of the literature review, frequency distribution of such articles from various journals, conference proceedings, and book chapters is depicted in the following Table 2.4.

Table 2.4 Number of articles by leading journals

List of Journals	Frequency

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	Journal of Cleaner Production	18
	Resources, Conservation and Recycling	15
	Computers in Industry	07
	Production Planning and Control	5
	Management Decision, International Journal of Information Management, Process Safety and Environment Protection	4 each
	International Journal of Production Research, Computers and Industrial Engineering, Journal of Manufacturing Technology Management, Renewable and Sustainable Energy Reviews, Robotics and Computer Integrated Manufacturing, Journal of Enterprise Information Management, International Journal of Production Economics.	3 each
Journals (Peer-reviewed)	International Journal of Operations and Production Management, Management Research Review, Ecological Economics, Engineering, Manufacturing letters, International Journal of Computer Integrated Manufacturing, Sage Journals, Journal of Marketing Channels, Business and Information Systems Engineering, Annals of Operations Research, Journal of World Business, Journal of Industrial Ecology, Journal of Environmental Management.	2 each
	Journal of Purchasing and Supply Management, Journal of Industrial Information Integration, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, Annual Reviews in Control, Journal of Mechanical Design, Science of the Total Environment, Omega, Engineering Applications of Artificial Intelligence, Supply Chain Management: An International Journal, Transportation Research Part E, Journal of Clinical Orthopedics and Trauma, Technology in Society, Journal of ambient intelligence and humanized computing, Waste Management, Journal of royal society publishing, Computer Communications, IEEE Computer Graphics and Applications, IEEE Communications Surveys and Tutorials,	1 each

	IEEE Access, Journal of Business Ethics, Journal of Systems and Software, Environmental Modelling and Software, Habitat International, Safety science, Government Information Quarterly, International Journal of e-Collaboration, Engineering Science and Technology: an International Journal, Journal of Material Cycle and Waste Management, International Journal of Advanced Operations Management, Computer Networks, Information and Management, Internet research, Journal of Industrial Engineering and Management, CIRP Journal of Manufacturing Science and Technology, Production and Management of Beverages, Journal of Manufacturing Systems, International Journal of Pure and Applied Mathematics, Journal of Systems Science and Systems Engineering, Journal of Computation Design and Engineering, International Journal of Engineering, International Journal of Management Reviews, International Journal of Industrial Ergonomics, Global Transitions, Procedia Computer Science, Management Information Systems Quarterly, Sustainable Energy Technologies and Assessments.	
Conference Proceedings and Book Chapters (Peer-reviewed)	Material Proceedings of Elsevier, Book Chapter/Reports and Industry Magazines.	95
Others (Workshop, Symposium, Summit)	European Summit on Future Internet Towards Future Internet International Collaborations and Dubrovnik International Economic Meetings	2
	Total Articles	185

2.4.2 Descriptive analysis

In order to understand the multi-criteria aspect of the concepts, research articles were selected from more than sixty-nine reputed journals. It can be observed that a major number of the

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articles have been published in leading journals, including the Journal of Cleaner Production, Resources, Conservation and Recycling, Computers in Industry, and Journal of Enterprise Information Management. Elsevier Science has the maximum number of publications, followed by Emerald Group Publishing and Springer.

2.4.3 Category selection

Strategic and operational types of decision variables have been used to categorize the selected articles, which are based on geographical locations and lot sizing of the articles. A conceptual framework has been developed for the adoption and implementation of Industry 4.0 and CE, which is shown in Figure 2.1. The developed framework for Industry 4.0 and CE have been classified into four categories. These categories are (i) Transition and integration; (ii) Adoption of combined factors and different issues; (iii) Implementation possibilities such as front-end technologies, integration capabilities, and redesigning strategies; (iv) Current challenges of Industry 4.0 and CE. It has been used by many authors, such as Kamal and Irani (2014), Govindan et al. (2015), Kamble et al. (2018b) and Tseng et al. (2018), in the area of Industry 4.0 and Supply Chain Management (SCM) respectively. Further, all these categories are included in single as well as multiple objective functions. Additionally, these categories are divided into sub-categories, i.e. "Adoption of combined factors and issues," which covered 38% of all articles. This implies that the mentioned categorization includes an adequate number of articles. Moreover, these categories consider numerous analyses such as case studies, surveys, experimentation, and simulation studies.

2.4.4 Content evaluation

The purpose of the content evaluation is to check the significance of the research outcome. A total of published articles were collected and analyzed for the initial cross-check of the content and relevancy for the research. The evaluation of the selected articles is generally based on the number of citations, number of volumes, website authenticity, and online feedback and support features (Bauer and Scharl, 2000). Most of the significant information of the individual articles was structured through the name of the journal, author name, keywords, publication date, page number, etc. Initial evaluations involved the categorization of the research articles through academics and researchers, further comparing these articles to ensure the enrichment of the present study. To enhance the validity of the research, data sets, journals along with the individual articles, the materials were cross-examined by four researchers using questionnaires and deep discussion simultaneously.

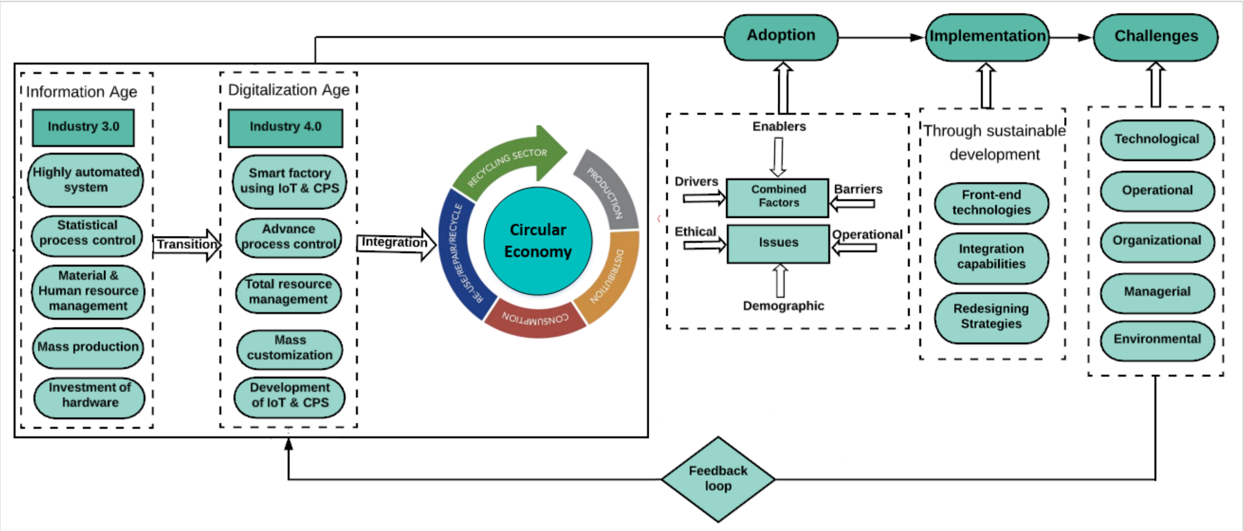

Figure 2.1 Transition framework of adoption and implementation for Industry 4.0 and CE

2.5 Select Issues of Industry 4.0 and Circular Economy

A detailed literature review has been carried out to identify the major issues in the area of Industry 4.0 and CE. Moktadir et al. (2018b) identified a lack of technological standards, which is the most prominent challenge of Industry 4.0 in the leather industry. Further, Kumar et al. (2020a) applied the DEMATEL approach and suggested that a lack of motivation from the

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customers is the leading challenge of Industry 4.0 in Indian SMEs. Rajput and Singh (2019b) used ISM hierarchical model and suggested that process digitalization and semantic interoperability are the prominent challenges of Industry 4.0 and CSC. Moreover, Ozkan-Ozen et al. (2020) applied the Fuzzy-ANP approach to prioritize the synchronized barriers of Industry 4.0 and CSC. Abdul-Hamid et al. (2020) used the fuzzy Delphi approach to identify the most suitable barriers to the palm oil industry in Malaysia. Further, lack of experience to lead digitalization transformations, lack of effective reverse logistic system, lack of cooperation with supply chain partners, lack of environmental guidelines and standards and minimal engagement of top management towards sustainable development are the other essential challenges for achieving a sustainable supply chain (Tseng et al., 2018, Dev et al., 2020, Sahu et al., 2022). However, it was found that factors, including adoption and implementation, circularity decisions, and performance evaluation of Industry 4.0 and CE are not covered in depth and need to be reviewed. For example, Patyal et al. (2022) reviewed 76 articles covering the entire area of Industry 4.0, CE and sustainability providing in-depth insight from different perspectives but reviewing very few articles on value analysis, performance evaluation, and circularity. Adoption and implementation, and circularity decisions are also not covered. Further, Industry 4.0 barriers are also reviewed that pose various challenges in the performance of Industry 4.0 and CE based supply chain. Khan et al. (2021a) have agreed that Industry 4.0 is the building block of CE and can explain the circularity of resources within operational systems of production and consumption. To expedite the understanding of Industry 4.0 concept, prior research has focused on the phenomenon of underlying the design principles and technology trends. Therefore, integrated Industry 4.0 and CE accelerate the sustainable innovation model, increasing end-of-life activities, optimizing wastages, and real-time monitoring of production and consumption operations. Zhou et al. (2015) have listed some of the major challenges of Industry 4.0 and CE. Sahu et al. (2023a) identified that circularity is one of the important aspects

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of Industry 4.0 and CE issues and needs more attention. Further, Kamble et al. (2018a), Luthra and Mangla (2018), Moktadir et al. (2018a), Rajput and Singh (2019), Yadav et al. (2020), Raj et al. (2020), Kumar et al. (2021), reviewed published literature on various aspects of Industry 4.0 and CE but select issues are either under-represented or not reviewed in their articles. The selected research articles are discussed and analyzed in this section to construct a holistic view of the recent and state-of-the-art studies in Industry 4.0 and CE on select issues. The results will clarify the current gaps in the literature and will provide the future scope of the research.

2.5.1 Adoption and implementation

In the adoption of Industry 4.0 and CE, various factors have affected the production process. In order to identify and analyze these factors critically, it will provide useful information for Industry 4.0 and CE implementation. The presence or occurrence of these factors can be converted into barriers or drivers. The combined barriers, drivers, and enablers are discussed in detail under this section.

2.5.1.1 Barriers to the adoption of Industry 4.0 and CE

Through a systematic literature review, various barriers have been identified and discussed in the study. Table 2.5 describes the combined barriers of Industry 4.0 and CE. It is observed that these barriers were specific to various sectors and countries in which the research was conducted. It is also noticed that a lack of investigation showed a combined study of the barriers. These barriers resulted in the identification of various challenges for the implementation of Industry 4.0 and CE. Furthermore, it is observed that most of the manufacturing industries and developing countries are rarely worked on these barriers.

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Table 2.5 Barriers of CE and Industry 4.0

Barriers	**Description**	**Sector**	**Countries**	**Authors**
Employment Disruption	The adoption of modern technology and digitalization is the cause of employment disruption.	Automobile and Manufacturing	India, Denmark and Italy	Kamble et al. (2018a); Stentoft et al. (2019)
Top management	Lack of involvement of top management, an attitude of workers, and company policies towards sustainability.	General	Australia, France and India	Caldera et al. (2019); Dubey et al. (2019)
High adoption and implementation cost	It is challenging to adopt and implement Industry 4.0 and CE technologies in SMEs because of high infrastructure costs, sensor technology, and material recycling cost.	Economic, Financial and Market	India, Japan, Norway and China	Kamigaki (2017); Jaeger and Upadhyay (2020)
Lack of customer awareness and government support	Lack of information about the modern technologies, lifecycle of the product, and government initiatives leads to the deprivation of natural resources, further causing environmental degradation.	General	India, USA, Bangladesh and Italy	Chauhan et al. (2019); Hanna et al. (2000); Cetrulo and Nuvolari (2020)
Collaboration Model	Lack of horizontal and vertical collaboration between humans and robots produces hazardous effects on the workplace.	Regulatory and Social	UK and Portugal	Despeisse et al. (2017); Castelo-Branco et al. (2019)

Technological and process integration	Lack of IT/digital technologies, data analysis abilities, and integrated back-end systems resulted in inadequate technology transfer, creating a gulf between design and manufacturing.	Information Technology	India, UK and Netherlands	Raj et al. (2020); Rajput and Singh (2019b)
Organizational and process conversion	Adoption of Industry 4.0 and CE concepts such as automation and recycling, the organizational function may be converted into a decentralized organization.	Smart factories and recycling plants	Sweden, Belgium and Brazil	Urciuoli et al. (2013); Rizos et al. (2016); Liao et al. (2017)
Lack of IT facilities and Internet	Inadequate IT support, lack of effective communication, and lack of tangible resources, i.e. data connectivity, act as crucial barriers.	Information Technology	China, UK and Portugal	De Jesus and Mendonça (2018); Dev et al. (2020)
Security and privacy	Unauthorized access to system data and networks from the server remains a significant barrier for the organization.	Cyber and Information technology	China and USA	Yu et al. (2015)
Seamless integration and compatibility	Extensive software support depends on decentralization that needs seamless integration to avoid faults and errors between production and business processes.	General	UK	Hart et al. (2019); Ancarani et al. (2019)

2.5.1.2 Driving forces for the adoption of Industry 4.0 and CE

The social, economic, and environmental changes led to support sustainability as well as the digitization of the current industry (Reischauer, 2018; Dachs and Jäger, 2019). The driving force of any industry is an important parameter that is used to run an entire organization without any difficulty. In case of Industry 4.0, the digitalization of the production process removes the boundaries between the physical and digital worlds. Therefore, digitalization is the principal driving force of Industry 4.0, while in the case of CE eliminating waste and continual use of resources are the principal driving forces. Many driving forces have been identified and discussed in the literature. These driving forces are described in Table 2.6. It is observed that these driving forces were specific to different sectors and countries on which the study was carried out. Further, the integration of these driving forces enhances product monitoring, service quality, and reverse logistic processes, which will be helpful in the waste recovery and maintaining product value chains. The literature review suggested that there was a lack of investigation showing a combined study of the driving forces.

Table 2.6 Driving forces of Industry 4.0 and CE

Major Driving Force	**Sub-Driving Force**	**Description**	**Countries**	**Authors**
Strategic planning	Business strategy development	Through R&D, develop short/long-term targets to fulfill customer requirements, improve time-to-market, and reduce cost and unusual wastage.	Sweden, Germany and India	Bechtel et al. (2013); Lasi et al. (2014); Singhal (2019)
Availability of information and resources	Information allocation of supply chain network	To withstand in the marketplace, the availability of right information about technical, financial, and human resources lead towards sustainability.	UK and Sweden	George et al. (2015); Lieder and Rashid (2016)
Profitability and efficiency	Organizational factors Technological	Reducing the failure rate, improving lead time, and ensuring reliable operation may increase productivity.	Serbia, Bangladesh and	Ilić and Nikoli (2016); Moktadir et

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	and process integration		Portugal	al. (2018a); De Jesus and Mendonça (2018)
Management reality	Market conditions and competitors	The market competition follows market trends that increase the pressure on competitors and develop a business innovation model.	China and Denmark	Agyemang et al. (2019); Pieroni et al. (2019)
	Opportunity for business innovation model	A demand for greater control and continuous monitoring of company performance.		
Collaboration between organizations	Leadership and Top management involvement	Collaboration and commitment from the top management of organizations play an essential character in sustainable manufacturing practices.	UK, South Africa, Malaysia and France	Walker et al. (2008); Mutingi (2013); Nordin et al. (2014); Dubey et al. (2019)
Technology	Technological and process integration, cooperation	Accessibility of the latest technologies that facilitate resource optimization, redesigning, and recycling of the product as input to other resources.	Serbia and Denmark	Ilić and Nikoli (2016); Stentoft et al. (2019)
Economic/ Financial/ Market	Development of the CBM	Sustainable design and maintenance increase product life, reduces the pressure on the environment, stimulates recycling abilities, and improve the supply chain.	Hungary, Brazil and Denmark	Demeter and Losonci (2019); Sehnem et al. (2019); Stentoft et al. (2019)

Social/Regulatory/ Cultural	Social awareness and environmental literacy	It is related to developing environmental standards, environmental legislation, and waste management directives.	Serbia, Bangladesh and Spain	Ilić and Nikoli (2016); Moktadir et al. (2018a); Garcia-Muiña et al. (2018)
Human resources	Increased innovation capacity and productivity	Through training and skill development program increases the efficiency of the workforce and modern ware technologies.	Germany and Italy	Müller et al., (2018); Gusmerotti et al. (2019)
Waste retrieval	Zero wastage	Through sustainable development, regeneration of natural systems, and the proper circulation of recycling and restoration of wastage.	Spain, Serbia and Hungary	Sevigné-itoiz et al. (2014); Ilić and Nikoli (2016); Horváth and Szabó (2019)

2.5.1.3 Enablers to the adoption of Industry 4.0 and CE

Various enablers have been identified and analyzed from the literature related to implementation of Industry 4.0 and CE. Digitalization can be understood as one of the important enablers of the CE because of its construction visibility and insight into products and resources, for example information on product location, condition, and availability. It has the facility to improve the supply chain processes, facilitate curricular activities, and optimize resource consumption. Moreover, the combined enablers discussed in the present study have capability to generate a supply chain more sustainable. Based on the literature review, combined enablers to integrate Industry 4.0 and CE are summarized in Table 2.7. It is observed that these enablers were specific to different sectors and countries on which the study was carried out. Additionally, these factors will help in achieving Industry 4.0 and CE goals by utilizing the capabilities of digitalization,

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reliability, and system integration.

Table 2.7 Enablers of Industry 4.0 and CE

Enablers	Description	Countries	Authors
Digitalization	Integration of digital technology into CE helps to identify failures and errors, ensures the quality of the product and services, and provides real-time information on the material collection.	Germany, Brazil and China	Bodrow et al. 2017; Cavalcanti et al. (2018); Tseng et al. (2020)
System integration	It strengthens the interrelation between digitalization and CE principle for the data transfer to ensure optimum utilization of resources and adopts sustainability principles for economic benefits.	Brazil and Portugal	Queiroz and Wamba (2019); Alcácer et al. (2019)
Continuous improvement	By adopting emerging technologies, specialized training skill programs and redesigning principles, continuous improvement can be possible for sustainable development.	Portugal and Australia	Leitão et al. (2016); Caldera et al. (2019)
Reliability and stability	The system needs to work together and fulfill its specified function without failure under stated conditions through data integration, digital twin, and preventive maintenance.	Italy and India	Borgia (2014); Rajput and Singh (2019a); Vaidya et al. (2018)
Technological roadmap	Adopting the latest technology primarily increases efficiency and product quality and also provides flexibility to the whole supply chain.	UK, Spain, Greece and India	Charro and Schaefer (2018); Garcia-Muiña et al. (2018); Saleem et al., (2020)
Government policy	Though government support for sustainable development	USA, China	Kshetri (2018);

and regulation	and making policies for recycling waste and adopting modern techniques for it.	and Malaysia	Bai et al. (2017); Ngan et al. (2019)
Preventive and Predictive maintenance	Preventive and predictive maintenance techniques were significant enablers for sudden breakdown safety, identifying errors, and reducing unnecessary wastage and cost.	Switzerland and India	Wortmann and Flüchter (2015); Rajput and Singh (2019a)
Collaborative manufacturing	Coordination between manufacturer and supplier, reducing delivery time, identifying new market opportunities, and working together to troubleshoot.	Sweden and India	Kalmykova et al. (2018); Muhuri et al. (2019)

2.6 Research Gaps

Research gaps were analyzed based on the literature review carried out for the research work. Theresearch gaps are enumerated and explained briefly in the following section.

- The implementation of Industry 4.0 and CE is in the nascent stage, and limited studies are available for the developing country in the manufacturing sector (Garcia-Muiña et al., 2018; Rajput and Singh, 2022).
- It is evident from the literature review that there are a few studies on the adoption and implementation of Industry 4.0 and CE, particularly in manufacturing sector of emerging economies (Ghobakhloo, 2018).
- The majority of the articles are focused on the case study and qualitative analysis rather than quantitative analysis. Therefore, more models need to be developed based on simulation and optimization studies that validate the existing theories from the perspective of Industry 4.0 and CE (Abdul-Hamid et al., 2020).
- It has been noticed that legal and ethical issues on adopting Industry 4.0 and CE have been

considered in a limited way and need to be explored extensively in the context of the Indian manufacturing industry (Kumar et al., 2020a).

- It is also observed that the effect of operational issues while adopting Industry 4.0 and CE are not covered in-depth and need to be explored in the context of the Indian manufacturing industry (Tseng et al., 2018; Sahu et al., 2022).
- It is revealed from the literature review that the demographical issues while adopting Industry 4.0 and CE are the major issues that are missing from the previous studies (Al-Fuqaha et al., 2015; Machado et al., 2020).
- The literature review also shows that most of the studies have individually identified and prioritized the major challenges of Industry 4.0 and CE. However, there is a lack of studies to establish the relationship between the challenges and solution measures for the Indian manufacturing industry (Moktadir et al., 2018; Kumar et al., 2021).
- The impact of front-end technologies with Industry 4.0 technologies in CE has not been explored much in previous studies (Frank et al., 2019).
- There are limited studies that consider the effect of Industry 4.0 technologies on product redesigning strategies. Therefore, product redesigning using Industry 4.0 technologies remains more and less unexplored (de Sousa Jabbour et al., 2018; Ellen Macarthur Foundation, 2017).

2.7 Concluding Remarks

The contemporary research in Industry 4.0 and CE is in the developing phase, and a lot of work is being carried out on various factors of Industry 4.0 and CE in various sectors. It is evident that research is diversified across the sectors and no single sector has been explored in-depth, particularly in developing economies like India. A perusal of the literature shows that select factors of Industry 4.0 and CE, such as adoption and implementation, circularity decisions, and performance evaluation of Industry 4.0 and CE are not explored in-depth. The research work

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explores and analyzes these factors in the context of the Indian manufacturing industry through survey method, case study, and development of models in subsequent chapters. The next chapter discusses the research methodology and framework to be utilized for the research work.

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Chapter 3

Research Methodology

3.1 Introduction

This chapter deals with the research methodology, which is to be followed for the research work. Research methodology is defined as "an operational framework within which the facts are placed so that their meaning can be seen more clearly". It is a "procedural framework within which the research is conducted". In this chapter, research objectives are established based on the research gap analysis and these objectives are enumerated in section 3.2. The research is based on the pragmatism research philosophy, which emphasizes on the research objectives as the primary component of research. A deductive research approach with a mixed-method approach has been adopted for the research. Each research method has its own strength but also has its shortcomings. The mixed method allows one to overcome the shortcomings of other methods and has several advantages, including the enhancement of validity and reliability of data coming from multiple sources. It has been utilized by many authors, such as Agrawal et al. (2018) and Rajput and Singh (2022) in the area of Industry 4.0 and CE. The survey method and the case study method along with methodologies for the development of models and decision frameworks have been utilized for the research work. Firstly, data were collected through a survey of the Indian manufacturing industry with the help of a questionnaire, and hypotheses were tested and results were analyzed. In second phase, case study method was utilized, which involves qualitative data collected through semi-structured interviews, and the results from the survey were validated through an in-depth analysis of the case study. The survey method and case study method are found to be dominant methodologies for examining Industry 4.0 and CE drivers, barriers, enablers and key challenges. This chapter also discusses the various methodologies used for developing the statistical models and decision frameworks.

3.2 Research Objectives

Based on the research gaps analysis discussed above following research objectives were established for the research work:

- To study and analyze the manufacturing industry from Industry 4.0 and Circular Economy perspectives.
- To identify challenges in the adoption and implementation of Industry 4.0 for manufacturing industry.
- To develop the model for the integration of Industry 4.0 and Circular Economy.
- To develop the framework for measuring the circularity of the manufacturing industry.

To achieve these objectives, a workflow of research methodology was developed, which is represented in Figure 3.1. A questionnaire was developed and pilot testing was carried out to improve the quality and contents of the questionnaire. Key challenges and issues were identified with the help of a literature review and discussion with the experts. A model has been developed for the prioritization of key challenges for the Indian manufacturing industry. These factors helped in understanding the manufacturing industry and development of the questionnaire. A survey was conducted to collect the information on numerous factors and strategic development of Industry 4.0 and CE in Indian manufacturing industry. Select factors for the research study were investigated through hypotheses testing of theoretical development of these factors. A case study was conducted subsequently for the validation of the findings related to these factors. Several models and decision frameworks have been developed for these select issues. The research methodology is discussed in detail in the following sections.

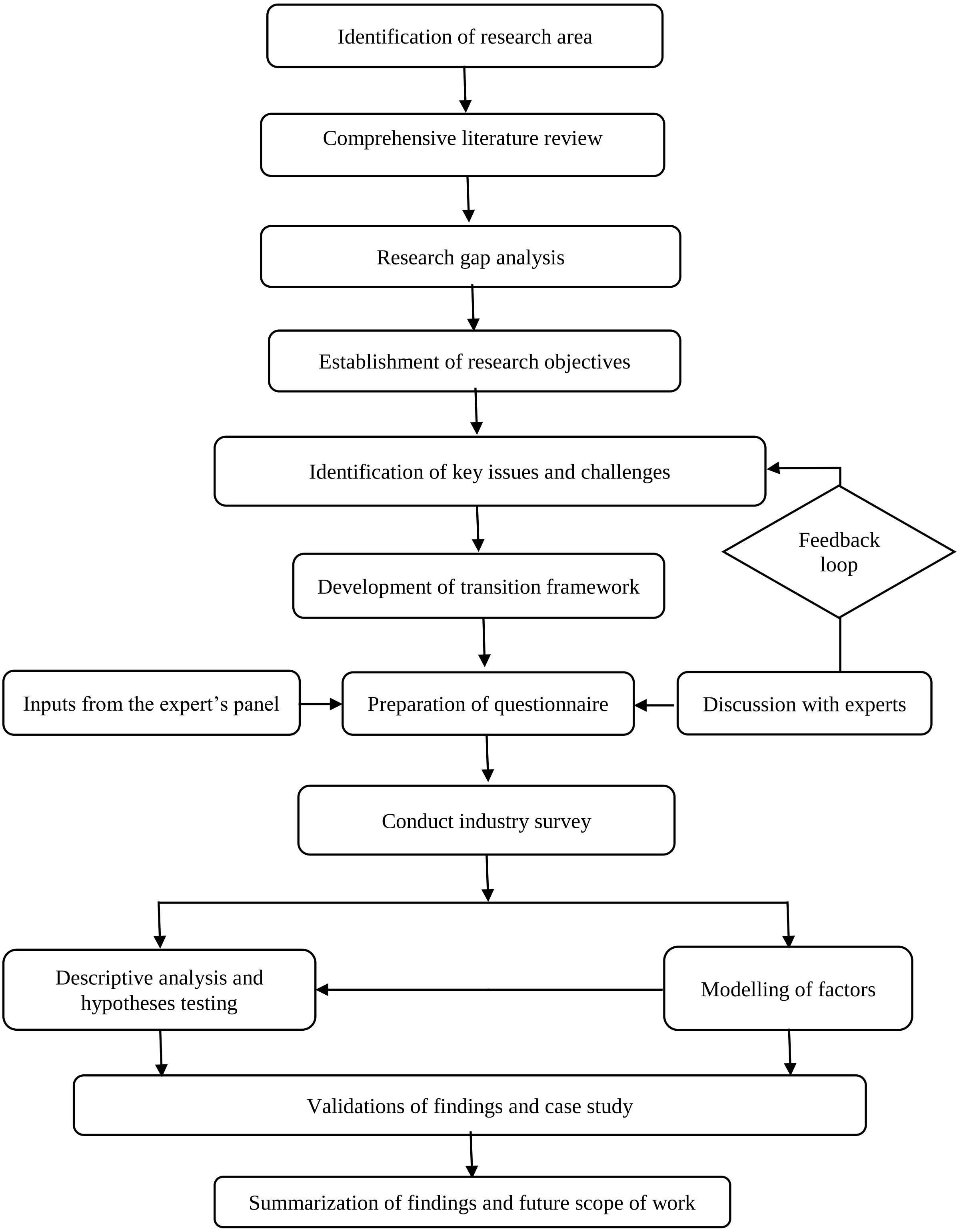

Figure 3.1 Workflow of Research Methodology

3.3 Methodology for Literature Review

A systematic literature review was carried out, and research gaps were identified. Research objectives were obtained through the research gap analysis. The research methodology is the systematic approach within which research work was proposed to reach a set of conclusions about these objectives. According to Saunders et al. (2011), there are six steps in the research methodology. The following steps of research methodology are described as follows.

- **Research philosophy**

The first step of the research methodology contains important assumptions, facts, theories, and frameworks. The considered philosophy influences the interpretations taken by the researchers. According to Saunder et al. (2011), the research philosophy is positivist, realist, subjectivist, objectivist, and pragmatist. The present study is considered the pragmatism research philosophy because it is the most important determinant of the research objectives.

- **Research approach**

As per the detailed literature review, two research approaches were found, i.e. deductive and inductive. The deductive approach considers the development of theories and hypotheses and designing the test strategy to measure the hypotheses. Moreover, the inductive approach considers the data collection and developing theories according to the result of data analysis. The present study is considered the deductive approach to with a multi-method approach has been used for the research. Initially, data were collected through research articles, books, and chapters.

- **Data collection**

The present methodology involves both quantitative and qualitative methods for data collection. Primary data was collected through a survey of the Indian manufacturing industry using questionnaires, personal interviews, and mailing of questionnaires. The results of the study were analyzed and utilized for the case method. In second phase, case study method was utilized, which involves qualitative data collected through semi-structured interviews. Both primary and secondary sources were used for the data collection and validation. The data collection and analysis are discussed in detail in the respective chapters.

- **Time horizons**

According to Saunders (2011), a longitudinal study is concerned with change and development over a certain period, whereas a cross-sectional study is concerned with the study of a specific phenomenon at a specific time. The majority of research work completed for academic courses must be time-constrained. Therefore, the research work has used a cross-sectional study.

- **Research methods**

There are a number of research strategies suggested by Saunders (2011). The research involves survey and case study methods along with various methodologies for developing the models and frameworks. The survey method helped in the quantitative assessment of the current Industry 4.0 and CE practices and issues related to Industry 4.0 and CE in the Indian manufacturing industry. Conversely, the case study method helped in qualitative in-depth assessment of a small set of cases. Although a single case is recommended for the case method if the researchers are associated with the organization (Yin, 2003), the single case study may be used in conjunction with survey method to clarify some of the results of the survey method more comprehensively. A survey method and a single case study have been utilized for the research work.

- **Survey method**

Survey method was utilized to explore the current Industry 4.0 and CE practices and issues in Indian manufacturing industry, and to test and validate the hypotheses through statistical analysis. The survey is most commonly used method in the area of Industry 4.0 and CE (Kiraz et al., 2020; Hussain et al., 2020; Khan et al., 2021b). It relies on the factual data and allows the data collection of adequate size in a very economical way through questionnaires. A survey of the Indian manufacturing industry was carried out for the data collection with the help of the questionnaire. The questionnaire was developed and administered through google forms, and responses were collected in the google forms. Questionnaire validity and reliability were ensured by checking non-response bias, Cronbach's alpha and other statistical measures. Data were analyzed to explore the current Industry 4.0 and CE practices in Indian manufacturing industry, and select factors were analyzed through a study of their relationship. Hypotheses were tested by using structural equation modelling (SEM) after ensuring their fitness for the test through measurement model analysis of different constructs. Partial Least Squares Path Modelling (PLSPM) was utilized for the research work because of its small size, and it combines the features of factor analysis and multiple regression. Although PLSPM is a conventional technique, its application in the field of Industry 4.0, CE and SCM were found recently by researchers such as Bag et al. (2020b), Hussain et al. (2020), Kiraz et al. (2020) and Khan et al. (2021b). The detailed systematic approach and application of survey method for the research work are discussed in Chapter 4.

- **Case study method**

Robson (2002) defined the case study as "a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence". The case study is utilized to have a thoughtful context of the research and the processes being practiced. According to Yin (2003), "A case study is an empirical enquiry that (i) Investigates a contemporary phenomenon within its real-life context, especially when, and (ii) The boundaries between phenomenon and context are not clearly evident". A case study is utilized as a research method if contextual factors are taken into account but at the same time limit the extent of the analysis. The case study method has been utilized frequently in the area of Industry 4.0 and CE (Sahu et al., 2023a). The research methodology adopted for the case study is based on a literature review and discussion with executives of the organization. A systematic approach was developed, which includes the establishing objectives, instrument development, data collection, data analysis, and dissemination. A single case with embedded issues was considered in conjunction with the survey method to access the findings systematically. The data for the case study were collected from both primary and secondary sources. Information and data collected from the field visits to the organization and other secondary sources were utilized to analyze the factors in Industry 4.0 and CE. The findings of the case study are explained in light of the findings of the survey of Indian manufacturing industry. The step-by-step procedure and application of case study for the research work are discussed in the Chapter 5.

- **Modelling based research methodologies**

The present research work has used several methodologies to develop models and decision frameworks. The methodologies utilized in this research work are discussed in the following sub-section.

- **ANP Fuzzy-TOPSIS methodology**

The selection of the implementation challenges of Industry 4.0 and CE depends on the various criteria and sub-criteria. Multiple criteria decision making (MCDM) is one of the powerful tools widely utilized for dealing with unstructured problems containing multiple and potentially conflicting objectives. Several MCDM approaches, such as AHP, Delphi, DEMATEL, and fuzzy TOPSIS are available to address such problems. The TOPSIS method was developed by Hwang and Yoon (1981) to provide solutions to the MCDM problems. TOPSIS is useful particularly when there are a large number of alternatives and criteria. In such cases, methods like AHP, which require pair-wise comparison are avoided. Also, TOPSIS has the fewest rank change reversals when an alternative is added or removed in comparison to other MCDM methods (Zanakis et al., 1998). The traditional TOPSIS method considers ratings and weights of criteria in crisp numbers. However, crisp data are inadequate to represent the real-life situation since human judgements are vague and cannot be estimated with exact numeric values. In such situations, the fuzzy set theory is useful for capturing the uncertainty of human judgments. Fuzzy logic has been combined and used along with TOPSIS known as fuzzy-TOPSIS methodology. If the parameters are independent, TOPSIS and AHP are used, which is not the case in the presented problem. When using the AHP approach, it is assumed that the criteria are independent of one another, which is not feasible in real-life applications. Similarly, analytic network process (ANP) has some advantages and disadvantages. According to Saaty (1996), ANP approach provides a hierarchical relation between criteria and sub-criteria and decision-making with feedback and dependence. As a result, a combination of ANP and Fuzzy TOPSIS multi-criteria approaches have been used for calculating the weights of the criteria and raking of the alternative, respectively. The detailed systematic approach and application of Fuzzy-TOPSIS methodology for the research work are discussed in Chapter 6.

- **Graph Theory and Matrix Approach**

Graph Theory and Matrix Approach (GTMA) has been utilized for the development of circularity decisions framework in Industry 4.0 and CE. Selection of the circularity option depends on the number of attributes and available options for the returned products circularity. Various MCDM approaches like TOPSIS, AHP, ANP, and DEA are available for providing solutions to such types of problems. TOPSIS and AHP can be utilized if the attributes are independent, which is not the case for proposed problem (Rao and Padmanabhan, 2006). While ANP does not represent a hierarchical relationship among attributes, DEA requires more computation and if the number of attributes are large, then DEA may be a poor discriminator of good and poor performers (Rao and Padmanabhan, 2006). GTMA does not have such limitations. Therefore, research work has utilized GTMA for the selection of best circularity alternative. GTMA is a systematic and logical decision-making approach. The advanced theory of graphs has been utilized for the modelling and analysis of various systems. It is proved beneficial for solving real-life problems in the field of science and technology (Chen, 1997, Jense and Gutin, 2000). Rao (2007), Agrawal et al. (2016), and Virmani et al. (2021) utilized GTMA for various supply chain studies. The detailed systematic approach and application of GTMA for the research work are discussed in Chapter 8.

3.4 Concluding Remarks

In this chapter, a research framework to achieve the research objectives has been developed. The research stages, such as research philosophy, research approach, data collection, time horizon, and research methods have been justified and developed for the research work. The research work reviews the salient features of the mixed research comprised of the survey method and case method. A systematic approach for validation of the findings of the survey method through case study method and subsequent development of models and decision frameworks are also discussed. The chapter also discussed about the justification of various methodologies, used for the development of models and decision frameworks on select issues of Industry 4.0 and CE. ANP Fuzzy-TOPSIS methodology will be utilized for the identification and prioritization of important factors in Industry 4.0 and CE. GTMA has been selected for the development of decision frameworks for circularity decisions and percentage of circularity, respectively. The chapter justified the use of these methodologies for the development of decision frameworks along with their utilization in past research in the area of Industry 4.0 and CE. In the next chapter, identification and prioritization of critical success factors for the Indian manufacturing industry are discussed.

Chapter 4

Descriptive Analysis and Hypotheses Testing

4.1 Introduction

It is found from the literature review that Industry 4.0 and CE play an essential character in managing the used product returns and end-of-life products both effectively. This chapter explores the current practices of Industry 4.0 and CE activities in the Indian manufacturing industry and evaluates the various factors in the industry. According to Díaz-Chao et al. (2021), the survey method is an appropriate tool for exploring an Industry and its Industry 4.0 and CE activities. The research work aimed to explore the Indian manufacturing industry through a survey of the industry. A survey was conducted in Indian manufacturing industry to explore the current trends, status, and factors related to Industry 4.0 and CE. Industry 4.0 and CE issues related to the key factors, circularity decisions, and value engineering implementation were explored, and hypotheses were developed to test the association of these issues with economic, environmental, and social performance of Industry 4.0 and CE. Hypotheses were tested after accessing the fitness of data through a measurement model. Complexities of relationships were studied with the help of Partial Least Square Path Modelling (PLSPM) approach of structural equation modelling, which takes into account the causal relationship among latent variables. PLSPM was utilized for the research work because of its small size, and it combines the features of factor analysis and multiple regression. The hypotheses development, observations from the survey, hypotheses testing, and findings of the study are explained in the following sections.

4.2 Research Model and Hypotheses Development

In earlier, Industry 4.0 and CE were considered cost-driven activities and focused mainly on economic aspects of the performance. In a survey of Indian manufacturing industry, Bag et al. (2020b) found that organizations are implementing Industry 4.0 and CE practices because of smart logistics and green manufacturing capability. Now, organizations are also addressing the environmental concerns through the contribution of Industry 4.0 and CE. Industry 4.0 and CE can make a significant contribution to the sustainable development of an organization (Sahu et al., 2023a). According to Rajput and Singh (2020), there is a need to explore the Industry 4.0 and CE planning and decision-making to improve the sustainability performance of an organization. However, there is little research on the social perspectives of Industry 4.0 and CE (Sahu et al., 2023a). The research work considers the all three perspectives of sustainability and evaluates the impact of various factors on economic, environmental, and social performance of Industry 4.0 and CE. There are a number of issues of Industry 4.0 and CE, which influence its performance. Research gap analysis demonstrates that circularity decisions and value engineering have not been explored much. Consequently, the research work developed the hypotheses on these factors to evaluate their impact on the economic, environmental, and social performances of Industry 4.0 and CE. Hypotheses are tested for the relationship of these issues with economic, environmental, and social performance of Industry 4.0 and CE based on a survey of the Indian manufacturing industry. The hypotheses developments are discussed in the following sub-section.

4.2.1 Hypotheses associated with Industry 4.0 and CE implementation

The drivers considered in this study such as SPD: Strategic Planning Drivers, which include SPD1: Business strategy development, SPD2: Real-time monitoring and control of manufacturing processes, and SPD3: Improve decision-making process. Further, TPI: Technological and Process Integration Drives include TPI1: Improvement of product customization, TPI2:

Increase of processes visualization and control, and TPI3: Profitability and efficiency. Similarly, MRD: Management Reality Drivers include MR1: Market conditions and competitors, MR2: Opportunity for business innovation model, and MR3: Availability of information and resources.

The barriers considered in this study such as TPI: Technological Process Integration Barriers, which include TPI1: High implementation and infrastructure cost (Agyemang *et al.*, 2019), TPI2: Lack of IT facilities and smart product manufacturing systems (Sahu et al., 2022), and TPI3: Security and privacy (Kumar et al., 2021). Further, SIC: Seamless Integration and Compatibility Barrier which include SIC1: Lack of process digitization and automation (Rajput and Singh, 2019), SIC2: Inadequacy in awareness and knowledge about latest technology (Raj et al., 2020) and SIC3: Lack of effective planning and top management commitment (Yadav et al., 2020). Similarly, HRB: Human Resource Barriers which include HRB1: Employment disruptions (Kamble et al., 2018a), HRB2: Lack of awareness about modern technology and skilled workforce (Chauhan et al., 2019) and HRB3: Lack of involvement of top management, attitude of workers and existing policies (Dubey et al., 2019).

The enablers were considered in this study such as TRE: Technological Roadmap Enablers, which include TRE1: CPSs, IoT and cloud manufacturing (Garcia-Muiña et al., 2018), TRE2: Reliability and scalability (Borgia, 2014), and TRE3: Integration and interoperability (Queiroz and Fosso, 2019). Further, SIE: System Integration Enablers which include SIE1: Integration and interoperability (Alcácer et al., 2019), SIE2: Global standard and data sharing protocols (Kalmykova et al., 2018), and SIE3: Government policy and regulation (Kshetri, 2018). Similarly, PPME: Preventive and Predictive maintenance enablers which include PPME1: Product Service System (Lin et al., 2019), PPME2: Continuous improvement (Leitão et al., 2016), and PPME3: Collaborative manufacturing (Muhuri et al., 2019).

The key challenges were considered in this study such as TC: Technological Challenges, which include TC1: Technological development (De Sousa Jabbour et al. 2018), TC2: Complexity in collaboration (Lu, 2017), and TC3: Data security and privacy (Gölzer et al., 2015; Kovacs, 2018; Radanliev et al., 2018). Further, OPC: Operational Challenges which include OPC1: Data management (Soualhia et al., 2017), OPC2: Big data and analytics (Tseng et al., 2018; Vaidya et al., 2018), and OPC3: Operational strategies for sustainable (Su et al., 2013; Schneider, 2018). Similarly, ORC: Organizational Challenges which include ORC1: Employment disruption (Zhou, 2015; Kovacs, 2018), ORC2: Collaborative model (Bressanelli et al., 2019; Tam et al., 2019), and ORC3: Decision-making ability (Wang et al., 2016; Martín et al., 2017; Luthra and Mangla, 2018). Also, MC: Managerial Challenge which includes MC1: Management support, MC2: Legal and ethical, and MC3: Demographic.

Information and data for the implementation of these drivers, barriers, enablers indicators, and key challenging factors were collected with the help of responses to the questions in Section 2 of the questionnaire. To test whether these barriers were positively associated with Industry 4.0 and CE, a hypothesis H1b was developed. The conceptual model of hypotheses development is shown in Figure 4.1. The hypothesis developed is as follows.

H1a. Drivers identified in the study are positively associated with Industry 4.0 and CE.

H1b. Barriers identified in the study are directly influencing with Industry 4.0 and CE.

H1c. Enablers identified in the study are positively associated with Industry 4.0 and CE.

H1d. Challenges identified in the study are directly influencing with Industry 4.0 and CE.

In the study, they reported that an organization could ensure sustainability even if they are implemented Industry 4.0 and CE practices. The research work evaluated whether these factors contributed to the economic, environmental, and social performance of Industry 4.0 and CE. The hypotheses are developed to test whether the benefits are positively associated with economic, environmental, and social performance of Industry 4.0 and CE. These hypotheses were tested in responses to questions in section 6 and section 8 of the questionnaire. The hypotheses developed are as follows.

H2a. Effectiveness of implementation decisions are positively associated with economic performance of Industry 4.0 and CE.

H2b. Effectiveness of implementation decisions are positively associated with environmental performance of Industry 4.0 and CE.

H2c. Effectiveness of implementation decisions are positively associated with social performance of Industry 4.0 and CE.

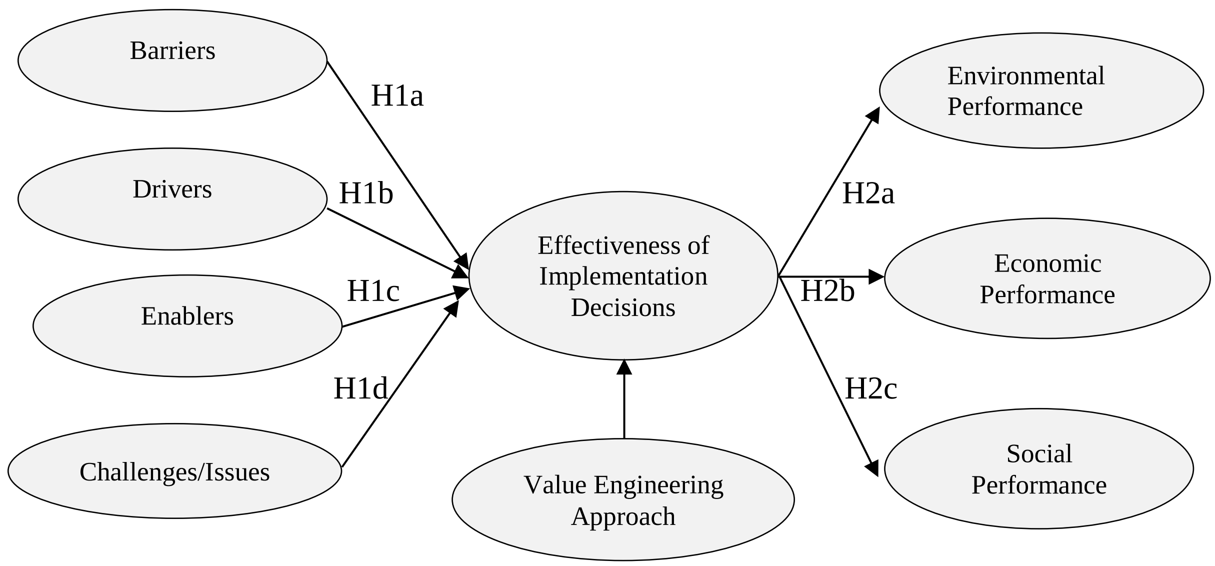

Figure 4.1 Model of hypothesized relationships

4.3 Data Collection

The following steps are followed for collecting the data through survey method.

4.3.1 Questionnaire development

A questionnaire was developed based on the comprehensive literature review and research gap analysis. The survey was divided into eleven sections aimed at gathering information in Indian manufacturing industry related to current practices, trends, and their opinion to measure the theoretical constructs of Industry 4.0 and CE. The four experts from the academics and five Industry 4.0 and CE practitioners from Indian manufacturing industry as pilot testing reviewed the preliminary draft of questionnaire. Reviewers evaluated the survey draft and commented on the clarity, and on the contents of the representativeness of the questionnaire. Suggestions were incorporated and questionnaire was improved before the distribution for the data collection.

The survey form was developed with the help of Google Forms. The survey questionnaire is available in Appendix A. The questionnaire mentioned that the individual responses and related information would be kept confidential.

4.3.2 Questionnaire administration

A cross-sectional quantitative survey method is utilized for data collection in the context of the Indian manufacturing industry. The present manufacturing industries have been selected because of the requirement of circularity performance, sustainable development objectives, and Industry 4.0 capabilities. The data was circulated to 220 manufacturing industries through Google Forms that implemented Industry 4.0-based technologies in their organization. The study also selected industries that have already utilized CE concepts in their industry. Further, additional 150 more emails were sent to academia and researchers in this area. A total of 390 emails were sent for conducting the survey. Out of 390 data samples, it is obtained a total of 120 responses filled and 42 were incomplete, therefore these incomplete responses were discarded. Therefore, the response rate of the questionnaire is around 30.77%. Malhotra and Grover (1998) suggested that more than 20% of responses are recommended in operational management research.

4.3.3 Profile of the respondent

In two phases, a total of 370 emails were sent to the Indian manufacturing industry for the survey. In total, 120 responses were considered appropriate for the research work. The demographic profile of respondents is shown in Table 4.1. The profile of the organizations and respondents are illustrated in Figures 4.2, 4.3, and 4.4. The number of employees and types of sectors are shown in Figure 4.2 and Figure 4.3, respectively. Organizations that participated in the survey belong to low to medium to large sizes, as found from the turnover shown in Figure 4.4. The respondents who have actually participated in this survey belong to Production Department, Manufacturing Department, Design and Development Department, Human Resource Department, Marketing and Sales Department, and Corporate Strategy Departments.

Table 4.1 Demographic profile of respondents

Types of Organization	Numbers	Percentage
Manufacturing	66	55.00%
Automobile	24	20.00%
Aerospace	08	6.674%
Food and beverage	12	10.00%
Marketing and Service	6	5.00%
Other	4	3.33%
Annual Turnover (INR in Million) of the Organization		
Less than 100	70	58.33%
In between 100-300	26	21.67%
In between 300-500	14	11.67%
Greater than 500	10	8.33%
Number of employees in the organization		

Less than 100	55	50.00%
In between 100-300	36	24.04%
In between 300-500	19	6.08%
Greater than 500	10	14.04%
Products/Services offered by the organization		
Service organization	30	25.00%
Products	90	75.00%
Total Industrial Experience		
≤ 5 years	54	45.00%
5-10 years	24	20.00%
10-15 years	32	26.67%
≥ 15 years	10	8.33%
Designation		
Vice President	44	36.67%
Director	30	25.00%
Executive	26	21.679%
Senior Manager	20	16.67%

Non-response bias with web-based survey was accessed by dividing the sample into two groups based on receiving date of the responses. The early response group consisted of 116 responses, whereas the late response group consisted of 120 responses. The t-test was used to determine whether there was a difference between the early and late response groups. It yielded no statistically significant difference between the mean of two groups ($p < 0.05$). Additionally, statistical tests show that there are no significant differences among samples in terms of the size of the organizations, the number of employees, and their designations. A five-point Likert scale with a level of agreement of respondents as 5 for Very Important, 4 for Moderately

Important, 3 for Absolute Important, 2 for Important and 1 for Little Important was used for the research work.

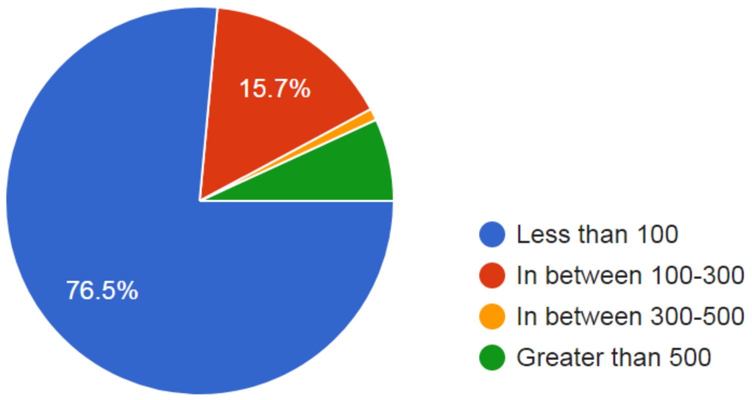

Figure 4.2 Total number of organizations and employees

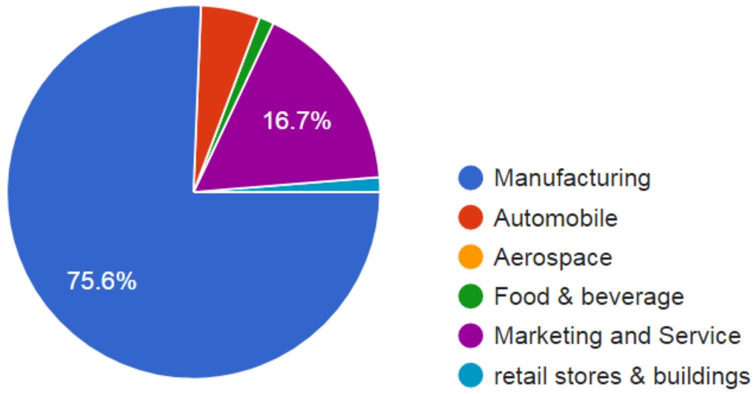

Figure 4.3 Type of sector

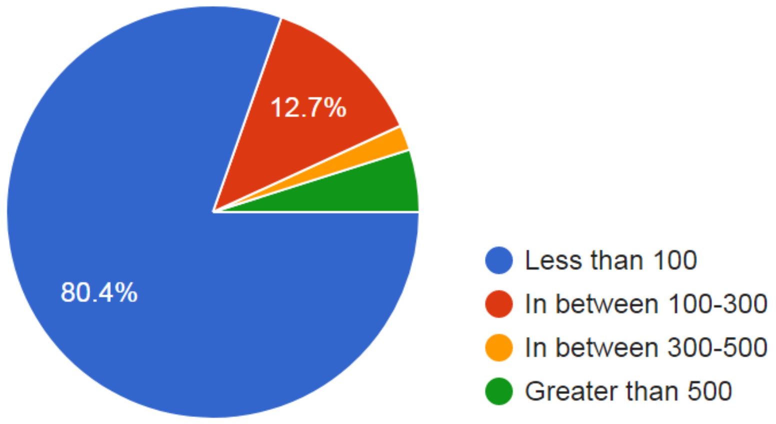

Figure 4.4 Annual Turnover (INR in Million) of the organization

4.4 Conclusions are drawn from the Survey

Observations from the Indian manufacturing industry were analyzed to understand the current practices, status, trends, and issues related to the Industry 4.0 and CE. Respondents were asked to express their opinion on a five-point Likert scale with the level of agreement of respondents as 5 for Very Important, 4 for Moderately Important, 3 for Absolute Important, 2 for Important and 1 for Little Important. Observations from the survey are analyzed and discussed in the following sub-sections. The results were analyzed and Cronbach's alpha was estimated for the constructs by using the software Smart PLS 3.0. The value of Cronbach's alpha ranges from 0.72 to 0.82, which is more than the minimum prescribed value of 0.5 for an exploratory study by Nunnally and Bernstein (1978). The values of mean and standard deviations are presented in the respective figures. The value of standard deviation is estimated to have an understanding of diversification among opinions and for any further analysis if needed.

4.5 Hypotheses Testing

The data collected was numerically coded in an MS Excel spreadsheet before it was transferred into the PLS Smart 3.0 software for further analysis. The data were visually scanned for errors and missing values for appropriate modification. Measurement models and structural models were analyzed by using structural equation modelling. Structural equation modelling has the ability to evaluate the measurement models within the same analysis. It is a systematic approach for analyzing causal models using latent variables with their observed indicators. There are two types of approaches in SEM. The first one is covariance-based (CB), which involves linear structural relations (LISREL) and Analysis of Moment Structures (AMOS). The second, one is partial least square path modelling (PLSPM) approach. The research work utilized PLSPM to test the hypotheses developed among constructs because of its ability to deal with small sample size, and non-normal distribution data. It has features of both factor analysis and multi-regression analysis. In PLSPM, a single observed indicator for a latent variable can be treated efficiently unlike in AMOS and LISREL where the numbers of observed indicators are restricted. The methodology involves a two-step approach in which the first measurement models are analyzed and after that, structural equation models are analyzed. PLS Smart 3.0 software analyzed the measurement models within PLSPM itself and provided the results with both in graphical and tabular forms. These approaches are discussed in the following sections.

4.5.1 Measurement model analysis

In order to test the hypothesis, validity and reliability of the constructs in the model are tested to ensure correct measurement by the observed variables. In a PLSPM analysis, the individual reliability of the item, the internal consistency and the convergent and discriminant validity are analyzed (Chin, 1998).

4.5.1.1 Individual Reliability

The individual reliability of items is examined to test whether a latent variable explains the substantial part of variance of its observed indicators. The individual reliability of each item for constructs with reflective indicators is evaluated by examining the loading of each indicator with the construct that it is intended to measure. The value of the standardized loadings must be equal to or greater than 0.5 (Falk and Miller, 1992).

4.5.1.2 Internal Consistency Reliability

The reliability of a construct tests the internal consistency of all the indicators while measuring the concept. It indicates that how rigorously the manifest variables are measuring the same latent variable. It can be measured in terms of Cronbach's alpha or composite reliability. Cronbach's alpha considers that all factor loadings are equally reliable and results in an underestimation of internal consistency reliability (Chin, 1998). Composite reliability is preferred in PLSPM because it considers different factor loadings and provides better results (Henseler et al., 2009). The internal consistency of proposed models is measured in terms of composite reliability. Nunnally and Bernstein (1978) suggested the minimum value of composite reliability as 0.7 for acceptance.

4.5.1.3 Convergent Validity

Convergent validity is tested to ensure that the construct represented by observed indicators has same underlying construct and has unidimensional characteristics. The convergent validity is analyzed by average variance extracted (AVE), which gives the amount of variance that a construct obtains from its indicators with respect to variance due to the measurement error. Fornell and Larcker (1981) recommend values higher than 0.5 for the measurement model to have convergent validity.

4.5.1.4 Discriminant Validity

Discriminant validity is the extent to which a latent variable account for the variance in observed indicators. To evaluate the discriminant validity, check if the average variance extracted (AVE) of the construct is greater than the square of the correlations between that construct and other constructs of the measurement model (Fornell and Larcker 1981). It indicates that one construct is different from any other construct.

4.5.2 Analysis of structural model

After analyzing the measurement model, the structural model is analyzed before examining the hypotheses for drawing any conclusion. The structural model is utilized to predict the hypothesized relations among latent variables for different constructs. PLSPM approach is selected because of exploratory nature of the study. Additionally, it does not require distribution restriction (normality) of the variables. The PLSPM approach was utilized and analyzed with the help of PLS Smart 3.0 software. Important indexes for structural model path modelling are explained and discussed in the following section.

4.5.2.1 Structural model path coefficient

Hypothesized relationships among constructs are estimated in terms of structural model path coefficients. The path coefficient value represents the strength of relationship between two constructs (Vinzi et al., 2010). The standardized values of path coefficients vary between -1 and +1. The values close to +1 indicate the strong positive relationships among constructs and are statistically significant. The values close to 0 indicate weaker relationships and are usually non-significant. To test the significance of various relationships among constructs, the research work used a 5% significance level for the critical value. If the empirical t-value is larger than the critical t-value, the hypothesis is accepted at this significance level.

4.5.2.2 Coefficient of determination (R^2 Value)

The predictive accuracy of the structural model is measured by explained variance (R^2) for the dependent latent variables. This is a squared correlation between the actual and predicted value of specified endogenous constructs. The standardized value of R^2 varies between 0 and +1, with higher values indicating higher predictive accuracy. As per Hair et al. (2010), independent variables with R2 values more than 0.7 are described as strong coefficient determinants, variables with values less than 0.25 are described as weak coefficient determinants, while 0.5 is considered moderate. However, there is no thumb rule for acceptable R^2 value because these acceptable levels depend on the complexities of the model and the research area. In addition, the change in the value of R^2 can be used to evaluate if an independent latent variable has a substantial effect on the dependent latent variable. This change, known as effect size f^2 is examined by omitting an independent latent variable and determining R^2 with and without an independent latent variable. The values of f^2 are 0.02, 0.15, and 0.35, respectively representing the weak, medium, and large effect of an exogenous latent variable on the specified endogenous variable.

4.5.2.3 Predictive relevance (Q^2 Value)

To analyze the stability of the estimations offered cross-validity redundancy (Q^2) developed by Geisser (1974) is utilized. The cross-validated redundancy approach considers both the measurement model and structural path model of data prediction and fits perfectly for structural equation path modelling. It measures the goodness with which the observed values are reproduced by the model and its parameter estimates (Chin, 1998). According to Henseler et al. (2009), a model has good predictive relevance if the value of Q^2 is greater than zero. In addition, the relative impact of predictive relevance can be measured in terms of size effect q^2, which is similar to the effect size f^2. The values of q^2 are 0.02, 0.15, and 0.35, respectively representing the weak, medium, and large effect of an exogenous latent variable on the specified endogenous variable.

4.6 Results

Three different structural models were analyzed by using the PLSPM approach. The measurement models and structural models are explained as follows.

4.6.1 Measurement model

The measurement models were analyzed before the structural model's analysis by using PLSPM. The measurement model developed for hypotheses testing was analyzed, and results are represented in Tables 4.1-4.6.

The model contained the relationship among factors influencing drivers, barriers, enablers, key challenges, VE implementation, and their relationship with economic, environmental, and social performance of Industry 4.0 and CE. Individual reliability of each item was accessed by standard factor loadings. As shown in Table 4.1, factor loadings for all items range from 0.687 to 0.940, which are greater than the threshold value of 0.5, suggested by Hair et al. (2006) and by Falk and Miller (1992). Individual reliability of each construct is supported. Internal consistency reliability for each of the construct is accessed by composite reliability (CR), which must have a minimum value of 0.7 for the acceptance (Nunnally and Bernstein, 1978). The CR value for all the constructs ranges from 0.899 to 0.935, which is greater than the minimum threshold value. AVE analyzed the convergent validity for all the constructs. The values for all constructs are higher than the minimum threshold value of 0.5 suggested by Falk and Miller (1992), which met the requirements of convergent validity. This indicates that all the latent variables explained more than 50% variance in their observed value. Correlation between the constructs and square root of AVE for each construct were analyzed for accessing the discriminant validity of the model. The results, shown in Table 4.2 indicates that square root of AVE values in all the cases are greater than corresponding off-diagonal values in the correlation matrix, which supports the discriminant validity of the model.

Table 4.2 Statistics results of a measurement model

Construct	Items	Construct Loading	Composite Reliability	Cronbach's Alpha	Average Variance Extracted
TPI: Technological Process Integration Barriers	TPIB1	0.85	0.901	0.860	0.704
	TPIB2	0.89			
	TPIB3	0.92			
SIC: Seamless	SIC1	0.91	0.898	0.844	0.741

Integration and Compatibility Barrier	SIC2	0.91			
	SIC3	0.90			
HRB: Human Resource Barriers	HRB1	0.89	0.911	0.855	0.667
	HRB2	0.87			
	HRB3	0.87			
SPD: Strategic Planning Drivers	SPD1	0.90	0.908	0.910	0.637
	SPD2	0.91			
	SPD3	0.90			
TPI: Technological and Process Integration Drives	TPL1	0.90	0.877	0.833	0.639
	TPL2	0.89			
	TPL3	0.88			
MR: Management Reality Drivers	MR1	0.90	0.910	0.826	0.622
	MR2	0.87			
	MR3	0.80			
TRE: Technological Roadmap Enablers	TRE1	0.88	0.768	0.899	0.725
	TRE2	0.90			
	TRE3	0.79			
SIE: System Integration Enablers	SIE1	0.88	0.880	0.852	0.704
	SIE2	0.92			
	SIE3	0.88			

PPME: Preventive and Predictive Maintenance Enablers	PPME 1	0.73	0.814	0.845	0.764
	PPME 2	0.90			
	PPME 3	0.89			
TC: Technological Challenges	TC1	0.85	0.709	0.695	0.663
	TC2	0.89			
	TC3	0.92			
OPC: Operational Challenges	OPC1	0.91	0.959	0.822	0.667
	OPC2	0.91			
	OPC3	0.90			
ORC: Organizational Challenges	ORC1	0.89	0.988	0.829	0.723
	ORC2	0.87			
	ORC3	0.87			
MC: Managerial Challenge	MC1	0.90	0.978	0.855	0.704
	MC2	0.91			
	MC3	0.90			
ECP: Economic Performance	ECP1	0.90	0.726	0.845	0.723
	ECP2	0.89			
	ECP3	0.88			

	ECP4	0.90				
	ECP5	0.87				
ENP: Environmental Performance	ENP1	0.88	0.886	0.910		0.667
	ENP2	0.89				
	ENP3	0.90				
	ENP4	0.79				
	ENP5	0.88				
SOP: Social Performance	SOP1	0.92	0.361	0.899		0.623
	SOP2	0.89				
	SOP3	0.92				
	SOP4	0.89				
	SOP5	0.92				

These findings fall within the acceptable limit prescribed by the researchers. The evidence of construct validity represents the adequate fit of measurement models (Iacobucci, 2010), and indicates for evaluation second part of the analysis, which is structural equation modelling analysis.

4.6.2 Structural equation model

In PLSPM technique of structural equation models, all the relationships among constructs related to hypotheses testing of models developed are analyzed. The structural model is analyzed by using the PLSPM approach with the help of Smart PLS 3.0 software. Figure 4.5 shows the structural equation model for the effectiveness of implementation decisions.

4.7 Results and Discussion

The findings of the hypothesis show that triple bottom line perspective of sustainability, i.e. economic, social and environmental factors affect the effectiveness of circularity decisions.

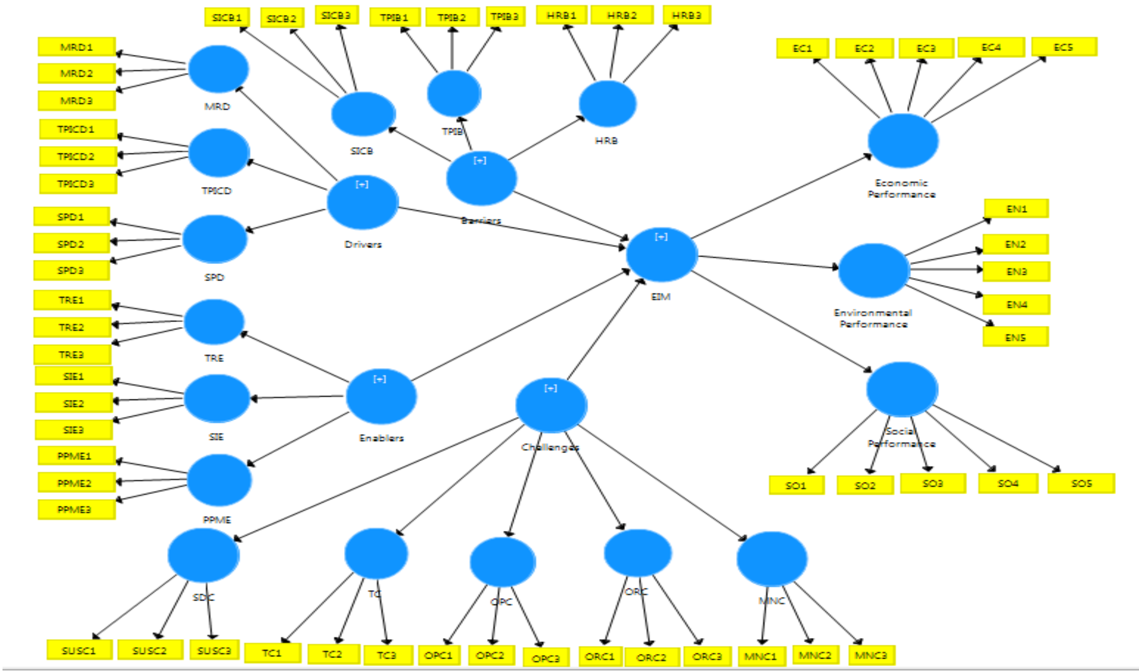

Figure 4.5 Structural equation model for circularity decisions

Circularity decisions are very important aspects of Industry 4.0 and CE implementation. The future of Industry 4.0 and CE depends on these decisions.

Table 4.3 Results of the structural model

Hypothesis	Path coefficient	t-statistic	P-values	f^2 effect size	q^2 effect size	Results
H1a	0.108	20.500	0.049	0.347	0.252	Accepted
H1b	0.526	0.980	0.021	0.412	0.197	Accepted
H1c	1.198	7.654	0.111	0.313	0.231	Accepted
H1d	0.647	16.063	0.000	0296	0.041	Accepted
H2a	1.098	96.439	0.004	0.304	0.229	Accepted

H2b	1.050	101.432	0.036	0.076	0.252	Accepted
H2c	1.124	23.089	0.021	0.345	0.197	Accepted

Note: Significantly lower than moderate value at $*p \leq 0.05$

The Model with a direct relationship among constructs indicated the adequate structural model fit. Hypothesis (H1a) predicted the influences of factors on accuracy in drivers of Industry 4.0 and CE. The results obtained from the Smart PLS 3.0 software are shown in Table 4.3 and Figure 4.4. The values of path coefficient, t-statistic, p-value, f^2 and q^2 are shown in Table 4.3 and fall within the limit as described in section 4.5 of this chapter. The path coefficient 0.108 is positive with a corresponding t-value of 20.500, which is higher than the critical value. The hypothesis is supported that factors influence the accuracy of drivers of Industry 4.0 and CE. Hypothesis (H1b) predicted the accuracy of barriers positively associated with the economic performance of Industry 4.0 and CE. The path coefficient 0.526, was also significant. Similarly, the third and fourth hypotheses (H1c) and (H1d) were also found to be substantial and support the respective hypotheses. Hypotheses (H2a, H2b and H2c) indicated that the effectiveness of implementation decisions are positively associated with economic, social and environmental performance of Industry 4.0 and CE. These results indicate that accuracy in implementing Industry 4.0 and CE is greatly influenced by the factors discussed above, and accuracy in implementing Industry 4.0 and CE is positively associated with the economic, environmental, and social performance of Industry 4.0 and CE.

The survey of the Indian manufacturing industry provided the data for this study, which explores the issues and their impact on the performance of Industry 4.0 and CE, and provides remarkable insight into the current practices of Industry 4.0 and CE. A survey was conducted, and responses were examined after satisfying all of the statistical standards. The findings from the survey indicate that most of the manufacturing industry in India has implemented Industry 4.0 and CE technologies in their production environment, while some of them are still dependent on importing the technologies due to many issues and challenges. Some of the major challenges while implementing Industry 4.0 are: lack of IT infrastructure, high initial and disposal costs, lack of collaboration and data sharing procedures, and lack of an effective reverse logistic system for implementing Industry 4.0 technologies for achieving CE practices in the organization. The findings of the survey show that Industry 4.0 and CE have become embedded in the strategic planning of many organizations. Several industries are implementing CE and Industry 4.0 techniques to provide better customer satisfaction, improve supply chain processes, identify failure and error, increase resource utilization, and maximize the circularity of resources and support the longer life of the products.

Chapter 5

Case Study

5.1 Introduction

This chapter deals with the case study, which is aimed at exploring the current practices of circular economy and value engineering and developing a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. A barrel manufacturing organization ABC has been considered for the illustration of the proposed methodology. The study aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. The case study is developed based on the research processes discussed in previous literature. The results of the study may improve the social, economic and environmental performance of the organizations.

5.2 Case Study Method

Case research is one of the effective tools for in-depth understanding and analysis of these issues.According to (Yin, 2003) "A case study is an empirical enquiry that (i) Investigates a contemporary phenomenon within its real-life context, especially when, and (ii) The boundaries betweenphenomenon and context are not clearly evident". The case study is used as a research method if contextual factors are taken into account but at the same time limit the extent of the analysis. Applying a flexible, sometimes even opportunistic research strategy is one of its major strengths, but it might also be a major weakness of case study research particularly, if the process is not well documented. The research methodology adopted for the

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research work is based on a literature review and discussion with executives of the organization. A step-by-step approach was developed, which includes the establishing objectives, instrument development, data collection, data analysis, and dissemination. A single case with embedded issues was considered a representative case of a wider group of cases for the research work. The data for the case study was collected from both primary and secondary sources. Information and data collected from the field visits to the organization and other secondary sources were used to implement the value engineering and CE in its manufacturing unit.

5.3 Profile of the Organization

A barrel manufacturing organization ABC has been considered for the illustration of the proposed methodology. The organization has been considered because it is the largest barrel manufacturer in India and has an ISO 9001: 200814000 and OHSAS 18001: 2007 certified unit. The ABC organization also validates all safety, health, and environmental norms and ensures the right product quality. The organization is a market leader in developing, producing and supplying barrels, with cover more than 32% market share. The organization has mainly focused on lean culture, continual improvement and eliminating waste. The organization was also awarded India Green Manufacturing Challenging (2020-21) and National Award for Manufacturing Competitiveness (2017-18). Organization has manufacturing, leather chemicals, industrial packaging, corporate travel and logistic services in India’s major cities, including Mumbai, Delhi, Kolkata, Chennai, etc. The organization has a major challenge in implementing VE and CE in its manufacturing unit. Currently, ABC is a semi-government organization with an annual turnover of around 16,000 Million ₹ and a profit margin of 2,300 Million ₹ as of the financial year 2020. In order to accommodate a wide range of products, including solid and

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liquid, hot and cold, as well as conical and cylindrical stackability types, ABC barrels are available in a variety of thickness configurations. During the case study of the organization, it is found that the organization generates a large amount of waste at the end of production. In addition, the existing machinery and processes consume a lot of power consumption which generates a large amount of CO_2 emissions and water consumption.

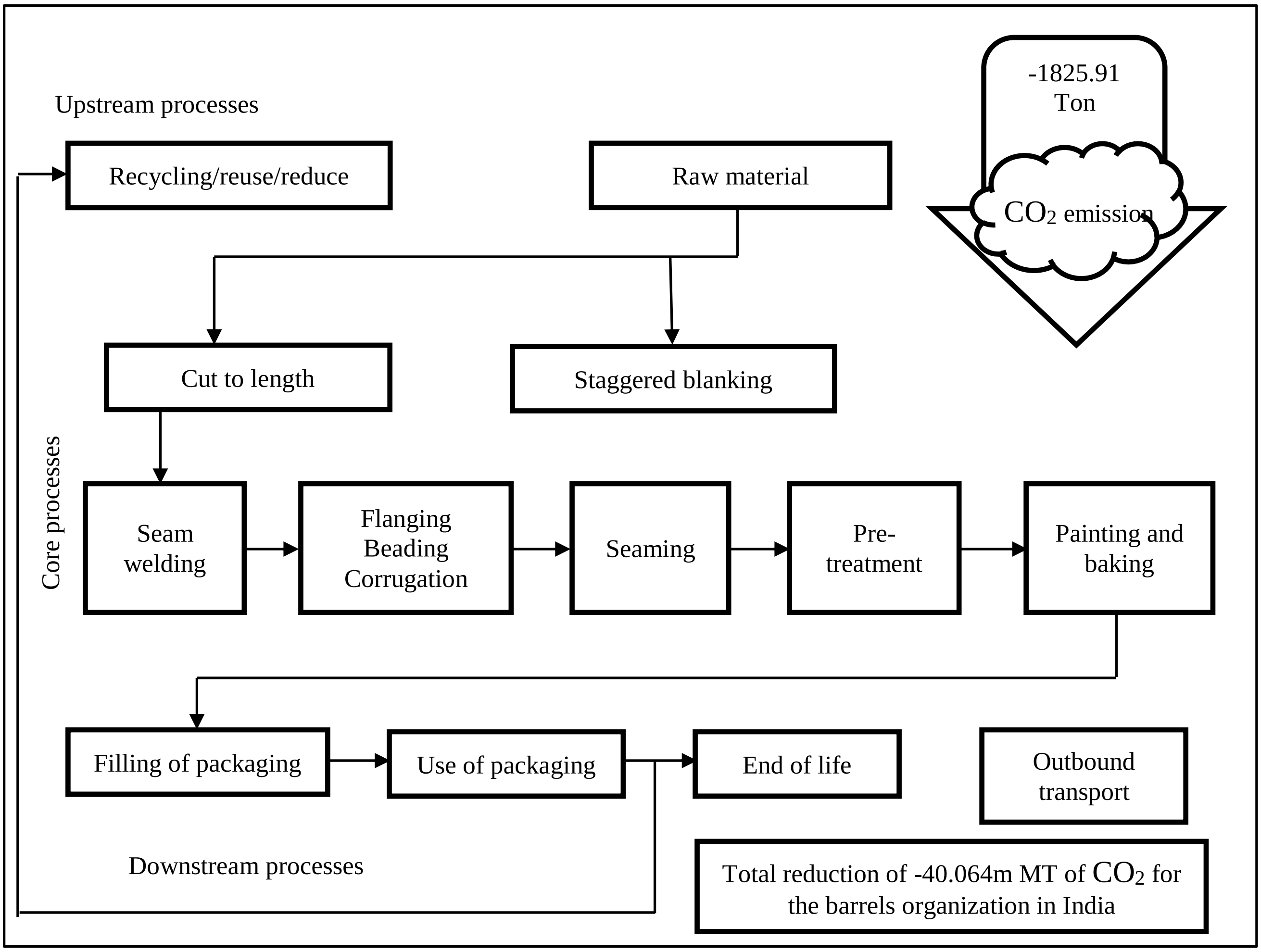

Figure 5.1 Product development processes of the barrel

Therefore, this study provides a significant effort in the barrel manufacturing organization to obtain a cost-effective and optimal solution for the continuous and large-scale waste retrieval of barrel trash. Figure 5.1 shows the product development process of the barrel. According to figures released by the human resource department, the current demand for CE and sustainable

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development products will expand by up to 35% over the next two decades. In this regard, organization ABC aims to adopt VE to analyze the wastes in the product development process and reduce them. Experts from the organization and the manufacturing industry have been selected for the case illustration. The experts have an average of about 15 years of industry experience in manufacturing, R&D, and marketing. Additionally, one expert in the field of CE was selected from academia. The experts have a prominent responsible position in their organizations, and their knowledge is considered to be adequate for the proposed research.

5.4 Value Engineering Approach

The proposed study has utilized VE for selecting the best alternative that reduces production costs and improves the performance of the products or processes. VE is a systematic and multi-functional approach that improves the performance of the products, processes and services. Further, it is also used to examine the factors that affect the cost of the product or process and increase competitiveness and the possibility of success (Cooper, 2017). According to Shen 1993, the VE is defined as "a systematic, function-oriented, problem-solving methodology to evaluate the functions and costs of a product system, service, supply or facility. The main objective of VE is to increase the sustainable value by achieving the strategic management principles defined by the customer or stakeholder at the lowest possible cost while meeting the required performance level (Setti et al., 2021). The majority of VE problems deal with the product development or product-level stages during the target costing process. Moreover, it is important to consider the environmental factors without violating quality, cost, reliability and performance during the product development process (Reche et al., 2020). There are seven steps of VE which are defined by Dell'Isola 1997. These steps are as follows:

- Functional analysis of parts/processes

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- Functional evaluation of each part/process
- Creative phase
- Evaluation phase
- Presentation phase
- Implementation phase
- Conclusion and future scope

The relationship between VE and CE for product development is in the nascent stage of development and very limited studies are available to consider it. Also, a framework considering the combined effect of VE and CE from the perspective of product development is rarely observed. Fig. 1 shows the framework that integrated VE, CE and product development processes. The objective of this integration is to make the product development process more sustainable with a reduction in wastage. According to Diaz et al. (2021), CE strategies provide decision-making support and a lifecycle assessment system for developing a sustainable product. The development of new products requires advanced technological development, high functional value and optimal resource utilization. Since, product development is an essential process for manufacturing industry growth and prosperity. According to Elmogahzy et al. (2019), product development is a process of developing or creating new products with additional or different characteristics than existing products in order to provide additional benefits to customers while maintaining or enhancing the profitability of the product's supplier. Further, the product development process is very challenging and expensive, mainly when it includes major changes in developing new products. A product development cycle is comprised of six essential stages that can mutually result in an economically sustainable product with maximum effectiveness. Figure 5.2 also

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presents the various stages involved in a product development process.

These stages include: ideation or generating a product idea, product definition or performance characteristic, prototyping, detailed design or analysis, validation or testing, and commercialization or marketing (Tyagi et al., 2015). The entire process of product development starts with market research and is completed with the delivery of product to the customer.

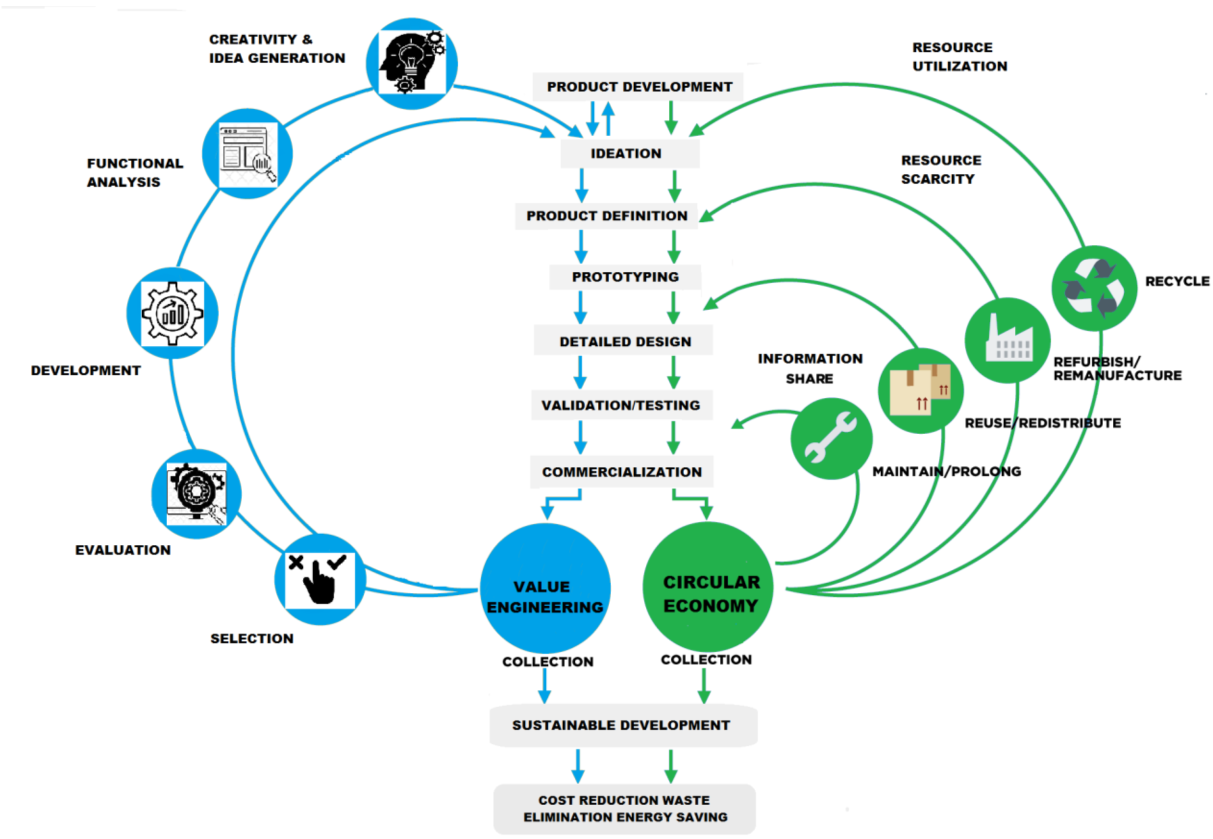

Figure 5.2 VE and CE framework for the product development process

Step 1: Functional analysis of parts/processes of barrel

In the first step of VE, the functional worksheet is prepared for each part/process associated

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with the barrel. It is a verb and noun type of definition of the individual parts of the barrel. The main function of the barrel is to store the semi-solids and liquids. However, in case of VE analysis, the focus is on individual parts/processes so that the overall cost and unusual wastage present in the system can be minimized. Table 5.1 shows the functional analysis of the different parts/processes of the barrel. There are nine parts/processes associated with the manufacturing of the barrel. Therefore, each part/process of the barrel has certain functions. This is the first stage of the evaluation. Subsequently, it is essential to identify which process/part of barrel manufacturing performs the basic functions and the secondary functions. The basic function of raw material is to hold the assembly. At the same time, it holds the other parts and provides strength and grip, so these are secondary functions of raw materials. Moreover, raw material is also used to assemble the entire structure of the barrel because in the functional analysis, raw material is used to hold the assembly together.

Table 5.1 Detailed function analysis of various parts of the barrel

Part name/ description	Quantity	Cost (₹)	Function		Part		Assembly	
			Verb	Noun	Basic	Secondary	Basic	Secondary
Raw material (CR steel)	1	1650.00	Hold	Assembly	X		X	
Seam welding	1	160.00	Provide	Joint		X		
Forming	4	100.00	Provide	Shape		X		
Assembly (Top and bottom)	2	60.00	Hold	Structure		X		
Pre-treatment	1	80.00	Provide	Strength		X		
Seaming	2	60.00	Provide	Leak-proof		X		

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Painting	1	80.00	Improve	Appearance	X
Baking	1	110.00	Improve	Strength	X
Filling of packing	1	80.00	Provide	Packaging	X
		Total = 2380.00 ₹			

In the subsequent step, the focus is on the cost because it is always considered in VE. There are two important things associated with VE, i.e. function and cost. Designers must take action to map these two things together. Table 5.1 also shows the total cost of various parts/processes of the barrel. There are nine processes and each process has a quantity and cost in ₹. The raw material has the highest cost, i.e. 1650 ₹ and the seam welding (electrical resistance welding) has the second-highest cost, i.e. 160 ₹. Similarly, the cost for other parts or processes is given, and the overall manufacturing cost of the single barrel is 2380 ₹. The fixed cost of each barrel is 120 ₹. Therefore, the total cost of each barrel is the summation of fixed cost, as well as a variable cost, i.e. 2500.00 ₹ (Eq. 1). Raw material, has a maximum cost, seam welding is slightly less, and assembly and painting is the least costly processes that go into the manufacturing of the barrel. Now, apply the VE concept to save costs for the ABC organization, which is making the barrel.

Total cost = Fixed cost + Variable cost (i)

Total cost = 120.00 + 2380.00 = 2500.00 ₹

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Step 2: Functional evaluation of different processes

In the VE, one function is interrelated with the other function, which is called the interacting function. Table 5.2 shows the functional evaluation of different processes of barrel manufacturing. It is found from Table 5.3 that, how A interacts with B, C, D, E, F, G, H and I. Grading is given on a 5, 4, 3, 2, 1 and 0 scale, where 5 is a major performance, 4 is important performance, 3 is moderate performance, 2 is medium performance, 1 is minor performance and 0 is equal performance. Table 5.3 shows the scale of weight analysis. Now, suppose A and B; if A is raw material and B is seam welding, the seam welding is performed on the raw material, so they have a very good interaction because one supports the other. As a result, it has assigned them a grade of 3, and similarly, if one H and I have a grade of 1, indicating that H is a baking process and E is packing, they are not in as much conflict or support with one another. Therefore, it has identified the given grading minor performance. In this manner, the tabular matrix is formed, which further gives relative weightage to the interactive functions or the interactive parts. Additionally, calculate the sum of all these gradings and give three, two, one and zero relative grading of the interacting products. Figure 5.3 shows the mudge diagram to evaluate the importance of each function. A has got the maximum weight (i.e., thirty-three weight), therefore, weight is assigned to the raw material. The overall weight percentage cost can be calculated based on the previous step, i.e. raw material and it is contributed to the overall cost of the product. Accordingly, the overall cost of the product is two 2380 ₹ and it can be seen that 1650 ₹ is being contributed by raw material only. It is very easy to calculate the percentage contribution of raw materials. The matrix method is used to determine both the relative importance of each factor and its percentage contribution to the total cost. These criteria of giving the maximum importance, medium importance, minimum importance, and equal importance.

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Step 3: Creative phase

In this phase, explore ideas on all the possible alternatives to achieve the required functions. Therefore, alternatives should be developed to perform the function at a lower cost, while maintaining the required performance. During the creative phase, it is determined that how to manufacture barrels in a cheaper manner and the techniques or options available to reduce the cost of the barrel without compromising the quality and performance.

Table 5.2 Functional evaluation of different parts/processes

Key letter	Parts/Processes	Function	Weight	Cost (₹)	% (Cost/total)
A	Raw material (CR steel)	Assembly	33	1650.00	69.34
B	Seam welding	Joint	09	160.00	6.72
C	Forming	Shape	13	100.00	4.20
D	Assembly	Structure	06	60.00	2.52
E	Pre-treatment	Strength	08	80.00	3.36
F	Seaming	Leak-proof	05	60.00	2.52
G	Painting	Appearance	05	80.00	3.36
H	Baking	Strength	00	110.00	4.62
I	Filling of packing	Packaging	01	80.00	3.36
	Total		71	2380.00	100

Table 5.3 Weight analysis

S no.	Weightage analysis	Points
1.	Maximum importance	5
2.	Medium importance	3

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3.	Minimum importance	1
4.	Equal importance	0

	B	C	D	E	F	G	H	I	
A	A5	A5	A5	A5	A5	A2	A5	A1	33
	B	B0	B3	B3	B3	B0	B0	B0	09
		C	C3	C5	C5	C0	C0	C0	13
			D	D0	D5	D0	D1	D0	06
				E	E5	E0	E3	E0	08
					F	F0	F5	F0	05
						G	G5	G0	05
							H	H0	00
								I	01

Figure 5.3 Mudge analysis to evaluate the importance of each function

The following alternatives are identified during the creative phase:

- Reduce the thickness and length of the sheet with a marginal reduction in volume.
- Material change: Change the material of the sheet from cold roll steel (CR steel) to DOS-A steel (RP79), which will increase the overall life of the barrel and eliminate the pre-treatment cost. The price of DOS-A steel sheet is slightly greater than CR steel sheet. However, the performance of DOS-A steel sheet is very high.
- Paint change: Change the type of paint from normal paint to PBSA paint which may increase the production of the barrel from 5 barrels/litre to 7 barrels/litre.
- Power consumption: During the manufacturing of barrel, it was identified that the maximum power was consumed by spot welding and electric resistance welding (seam welding) processes. The apparent power requirement is around 143 KVA using a 1-phase AC welding transformer with a 2-phase supply. Also, the rate of production per day is

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160 barrels. Therefore organization needs to implement new machinery that may increase production rate and reduce the power consumption.

- Environment protection and sustainability: Make the product sustainable, i.e. reduce CO_2 emissions, cost and create an environmentally-friendly product. The organization has the cumulative capacity to offset around 400 tons of CO_2 each year. By installing 230 KW_p grid-tied solar generation systems in the organization (130 KWp solar generation systems were installed in February 2014 and further additional 100 KWp solar generation systems were installed in Jan 2017) 2,24,021 Units of electrical energy were generated as of 13 March 2021 from the solar generation Unit during FY 2020-21, which is 25% of the total energy requirement of the unit, which is equivalent to ₹ 22.73 Lacs. The maximum power generated through solar power is 28,000 units in the months of January, February and Mach, while 20,000 units are generated in December month due to fog and dew formations.
- CO_2 emission: ABC organization has cumulatively generated solar energy of 4,69,522 units in the fiscal year 2019-20, which prevented 800 tons of CO_2 emission from the manufacturing cold chain operation. The organization is also working on zero time lost injury for the 3rd consecutive year. Further, for the baking process of barrels organization may have implemented Piped Natural Gas (PNG) instead of conventional High-Speed Diesel (HSD). The conversion from HSD to PNG is shown in Table 5.4. It is found that PNG fuel has several benefits, such as being eco-friendly, convenient, economical, safe and reliable as an energy source.

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Table 5.4 Conversion from HSD to PNG

Parameters	PNG	Diesel
Calorific value	9000 Kcal/SCM	8800 Kcal/Ltr
CO_2 emission	1 SCM PNG =1.71 kg/SCM	1 Litre Diesel = 2.66 kg/Ltr

**Conversion: 1 Litre Diesel = 1 SCM (Standard Cubic Meter) PNG

- Water consumption: Reduce water consumption through an effluent treatment plant (ETP) process that will reduce waste water through treatment processes, which is further utilized for horticulture and green belt irrigation. The organization consumes 2000 litres of water per day. By implementing the ETP system, only 4% of water is wasted, and 90% of water is further utilized for horticulture and green belt irrigation. The remaining 6% treated water is used for sludge output generation in a solid form which is equivalent to 100-150 kg/month. Also, sludge water is sent to an external party (GEPIL) on a half-yearly basis for disposal.
- Social impact: Regular skill development training and awareness programs to sensitize people are being conducted for employees in the areas of corporate social responsibility (CSR) and sustainable development. Long-term CSR and sustainable development initiatives have been intended to minimize the carbon footprint related to the To/Fro transportation of containers from Kolkata Port to the container freight station (CFS). Further, the organization has developed an integrated railway siding between Kolkata port and CFS.
- Raw material utilization: Utilize waste pieces of raw material in the production of key locks and bicycle bells.

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- Lightweight: Implement a lightweight DOS-A barrel by reducing thickness and length, which saves a significant amount of raw material consumption and weight of the barrel.

Step 4: Evaluation phase

The value gap has been calculated in the evaluation phase by comparing the existing cost with the estimated cost. There are a total of nine processes, i.e. A, B, C, D, E, F, G, H, and I. The existing cost of the barrel is 2380 ₹. The first part/process of barrel manufacturing is A, i.e. raw material, which has the basic function of holding the entire assembly. The existing cost of the raw material (CR steel) is 1650 ₹. Now, the worth is also calculated using the tentative alternative. If the material of the barrel is changed from CR steel to DOS-A steel, the overall performance of the barrel can be increased. Moreover, DOS-A steel provides highly rust-preventive and direct painting properties. As a consequence, the cost of pre-treatment process is saved. Further, the cost of DOS-A steel sheet is slightly higher than CR steel. The estimated cost of 1 MT of CR steel is around 66,000.00 ₹, while the cost of 1 MT of DOS-A steel is 70,000.00 ₹. For a single barrel, the raw material cost of CR steel is 1650.00 ₹, while the cost of DOS-A steel is around 1273.00 ₹. Due to the high strength of DOS-A steel, a 0.90 mm (21 gauge) sheet performs the same function as CR steel without compromising the effectiveness, reliability, toughness and dependability of the sheet. Further, the length of the barrel changes from 1330 mm to 1220 mm with a marginal reduction in volume. Consequently, material waste per coil is reduced (saving the raw material wastage). Therefore, while considering the 1 mm thickness sheet, 1 MT of CR sheet produces 50 barrels per MT, whereas 1 MT of CR steel produced 40 barrels per MT previously. Similarly, while considering the 0.90 mm thickness sheet, 1MT of DOS-A sheet produces 55 barrels per MT. By conducting a destructive test of the barrel from a height of 1.5 m height, the strength as well as the performance of the barrel

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remain unchanged. The destructive test is used to calculate the point of failure of the material. Additionally, the weight per barrel is reduced from 22±0.5 kg to 18 ±0.5, i.e. 4 kg weight reduction per barrel by considering the 1 mm (20G) thickness of the CR steel sheet. Similarly, the weight per barrel is reduced from 22±0.5 kg to 17±0.5, i.e. 5 kg weight reduction per barrel by considering the 0.90 mm (21G) thickness of DOS-A steel sheet. Using the destructive test for CR-steel of thickness 1.0 mm and DOS-A steel of thickness 0.90 mm, it is able to satisfy all the mechanical properties of steel and the required certification. The value gap of tentative raw material is 377 ₹ and it gives the rank I. It can be observed that process E, i.e. pre-treatment, is not required for the DOS-A steel. Therefore, it is being suggested that pre-treatment of DOS-A steel can be avoided so this particular process can be eliminated, however it is not affecting the overall performance of the barrel. The estimated cost of saving the pre-treatment process is around 80 ₹. Similarly, by changing the type of paint (G process) from ordinary paint to PBSA paint, the production rate increases from 5 barrels/litre to 7 barrels/litre. The current cost of paint is around 80 ₹ per barrel, but by introducing PBSA paint the cost is reduced by 68 ₹ per barrel. Therefore, the value gap is 12 ₹.

Furthermore, by installing PNG instead of conventional HSD systems makes the cost-savings during the baking process (H process) is around 12 ₹ per barrel. The procedure for calculating the reduction in CO_2 production is as follows:

For plain and lacquered barrels, the existing HSD produces CO_2 emissions per year of 290.17 Ton and 342.39 Ton, respectively. Using Eq. (ii), diesel consumption per year for plain barrels was found to be 109086.12 Ltrs and for lacquered barrels was found to be 128716.35 Ltrs. Similarly, using Eq. (iii), the PNG consumption per year for plain barrels was found to be 109086.12 Ltrs and for lacquered barrels was found to be 128716.35 Ltrs. Further, total CO2 emission from diesel was found at 290.17 Ton using Eq. (iv) and CO2 emission from PNG

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was found at 186.54 Ton using Eq. (v). Therefore, the total reduction in CO_2 emission for plain barrels was 103.63 Ton and the total reduction in CO_2 emission for lacquered barrels was 122.28 Ton. The total reduction in CO_2 emissions using PNG was found at 225.91 Ton by utilizing Eq. (vi). Table 5.5 shows the calculation of the reduction of CO_2 emissions.

Diesel consumption per year = Diesel Consumption per barrel * barrels production per year (ii)

PNG consumption per year = PNG consumption per barrel * barrels production per year (iii)

Total CO_2 emission from diesel = Diesel consumption per year * CO_2 emission from diesel (iv)

Total CO_2 emission from PNG = PNG consumption per year * CO_2 emission from PNG (v)

Total reduction in CO_2 emission = Reduction in CO_2 emission from Plain barrel + Reduction in CO_2 emission from Lacquered barrel (vi)

Table 5.5 Reduction in CO_2 emission

Sales volume (2020-21)	Barrels	Yield Diesel (Ltr/Brl)	Yield PNG (SCM/ Brl)	Diesel		PNG		Reduction in CO_2 emission (Ton)
				Total Diesel Consumption (Ltrs.)	CO_2 emission from Diesel (Ton)	Total PNG Consumption (SCM)	CO_2 emission from PNG (Ton)	
Plain barrel	303017	0.36	0.36	109086.12	290.17	109086.12	186.54	103.63
Lacquered	12258	1.05	1.05	128716.35	342.39	128716.35	220.10	122.28

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barrels	7					
Total	42560 4	237802.47	632.55	237802.47	406.64	225.91

Similarly, during the manufacturing of the barrel, maximum power is consumed by spot welding and electric resistance welding processes (also called seam welding process) and the cost of the existing seam welding process is around 160 ₹. Also, the existing machine requires a 250 KVA 1-phase AC welding transformer with a 2-phase supply, 143 KVA at 370-ampere current. Consequently, this high ampere current required huge power consumption, which affected the overall cost of the production. To address these production issues, the organization imported a 3-phase Arplas Synchron AC welding controller with a 1-phase AC welding transformer, which reduces the current machine's power consumption by 70 amperes. Therefore, the total power saved by implementing the single process is around 100 KVA. Further, the existing welding machine produced 160 barrels per day because existing machines take two processes, i.e. spot welding and electrical resistance welding to make the welded joint. It also requires additional space, labour, machinery and power consumption at a very slow rate. While implementing the new Arplas Synchron AC welding, the production rate increased from 160 barrels per day to 400 barrels per day. Consequently, the cost of seam welding process is reduced from 160 ₹ to 110 ₹. Additionally, the cost of implementing the new machine will be balanced by 20% per year.

Electric energy savings:

Existing machine: 250 KVA 1-phase AC welding transformer with 2-phase supply

Current (I) = 370 A

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V/g (V) = 390 V

Apparent power (P) = V * I = 143 KVA

By implementing a 3-phase Arplas Synchron AC welding controller with a 1-phase AC welding transformer:

Current (I) = 70 A

V/g (V) = 390 V

Apparent power (P) = $\sqrt{3}$ V* I = 47 KVA

Saving in power = 100 KVA

Similarly, the value gap has been calculated for the other processes or parts of the barrel. Three processes may save 569 ₹ for manufacturing the barrel during the valuation phase by implementing tentative alternatives. Table 5.6 shows the functional cost worth analysis of the barrel manufacturing. It is calculated that the estimated cost is 1811 ₹ while the existing cost is 2380 ₹. Therefore, the value gap between the existing and estimated designs is 569 ₹. Also, without compromising the performance of the product, the estimated design can save some cost elements by switching to alternative materials, changing alternative designs, and changing the gauge thickness of the sheet. Therefore, it is found that evaluating an existing design always leads to better outcomes. A total of five processes have a higher value gap which means there is a huge scope for putting efforts into reducing the cost of the product without compromising the performance.

Table 5.6 Function cost worth analysis

Part name/ description	Function		Existing cost in ₹	Worth		Value gap	Ranking
	Verb	Noun		Tentative alternative	Estimated cost in ₹		

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Raw material (CR steel)	Hold	Assembly	1650.00	Raw material (DOS-A steel)	1273.00	377.00	I
Seam welding	Provide	Joint	160.00	Seam welding	110.00	50.00	IV
Forming	Provide	Shape	100.00	Forming	100.00	00	VI
Assembly	Hold	Structure	60.00	Assembly	60.00	00	VII
Pre-treatment	Provide	Strength	80.00	Pre-treatment	00	80.00	II
Seaming	Provide	Leak-proof	60.00	Seaming	60.00	00	VIII
Painting	Improve	Appearance	80.00	Appearance	68.00	12.00	V
Baking	Improve	Strength	110.00	Strength	45.00	65.00	III
Filling of packing	Provide	Packaging	80.00	Filling of packing	80.00	00	IX
		Total	2380.00		1811.00	569.00	

Additionally, in the evaluation phase, a comparison is made between the existing design and the modified design of the product. The result shows that the design change saves 569 ₹. Therefore, design one part/process, i.e. existing and redesigned parts/processes using that creative phase. Consequently, it has a redesigned part, and then there is a value gap, i.e. modified design. As a result, the total savings is 569 ₹. This 569 ₹ should not be at the cost of any reduction in performance. It will evaluate the designs based on their hardness, lightweight, toughness and aesthetics.

- Parameters

A. Hardness

B. Lightweight

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C. Toughness

D. Aesthetics

- Alternative – I: Reduce the thickness of the raw material, i.e., sheet from 18 gauge (1.20 mm to 1.25 mm) to 20 gauge (0.97 mm to 1.0 mm) and reduce the length of barrel from 1330 mm to 1220 mm with marginal reduction in volume.
- Alternative – II: Change the raw material from CR steel to DOS-A steel. Further, reduce the thickness of the raw material, i.e., sheet from 18 gauge (1.20 mm to 1.25 mm) to 21 gauge (0.90 mm to 0.80 mm), reduce the length of barrel from 1330 mm to 1220 mm with marginal reduction in volume.

The alternative-I is to change the thickness and length of the sheet, i.e. this is one alternative-I as compared to the existing design and the alternative-II is to change the raw material as well as thickness of the sheet wherever required. Therefore, in the creative phase it is observed that there is a scope to redesign the product in such a manner that it can save some cost. In worth, it now has the worth cost, worth function, and cost-worth analysis. It has been discovered that there is a possibility or opportunity to save 569 ₹ as a result of the product's design changes or redesign. In the subsequent stage, three design changes or modifications are available. The first one is the existing design, the second is the design with a change in the material of the sheet, i.e. using a different material for the sheet, and the third is a reduced thickness of the sheet. Now, it has three designs that can be compared with the existing design. The second is the design with the changed material of the sheet, i.e. DOS-A steel, and the third is the reduced thickness and length of the sheet. Now, it has to compare these three designs using the same matrix technique. It can calculate the weightage of the parameters, there are four parameters A, B, C and D. It is found that the weightage for A and B is 4, implying that hardness and

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lightweight have significant interactions. Similarly, for C and D the weightage is given 1, which means toughness and aesthetics do not have much interaction with each other. Therefore, calculate the score of A and B, which established a very good interaction with hardness and lightweight. Likewise, it has to be considered along with A and C, i.e. hardness and toughness. It also has medium interaction 3. Likewise, add all of these scores together, i.e., 4 + 3 + 3 = 10, 3 + 2 = 5, 1 and 1. The total weightage is given to the various factors, i.e. A has been given 10, which means hardness is the final score of 10, i.e. the highest rating factor or the highest weightage factor, then a minimum weightage factor D is the aesthetic. In the case of a barrel, the product is always used to store the oils or semi-solid products; therefore, aesthetics is not a very important or prime criterion for the analysis. However, hardness, lightweight and toughness are very important criteria. The first highest score goes to hardness, second goes to lightweight, third is toughness and fourth is aesthetics or the appearance. In this manner, calculate the final score or the weightage of the various parameters, then compare these parameters. Now, it has four parameters and these parameters have to be compared with the three designs. One is the existing design, the second is the design with a reduced thickness of the sheet, and the third is a design with a changed material of sheet with varying thickness. Let us observe that these three designs have to be compared with each other. The existing design is the first design, then changes the material of the sheet is from CR steel to DOS-A steel and reduces the thickness of the sheet from 18 gauge to 20 gauge. Hardness, lightweight, toughness, and aesthetics score 10, 5, 1 and 1. Subsequently, the scores are given as follows: 5 for excellent, 4 for very good, 3 for good, 2 for fair and 1 for poor. Data is collected from the manufacturer, the customer, and the marketing people where they can use these products for a specified period, and data is collected from them, and scores are assigned. Table 5.7 shows the evaluation matrix for existing and proposed parts/processes. For the existing design and

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hardness point of view, a score of 4 is given for alternative-I and a score of 5 is given for alternative-II. Therefore, multiplying the weightage factors 4 and 5 a score of 40 on hardness for the existing design is observed. For a modified design that is also reduced in the thickness and length of the sheet and get a score of 40, and for the changed material and reduced thickness of the sheet get a score of 50. Therefore, all three designs' hardness value is maximum for the alternative-II, i.e. 50 followed by alternative-I (40) and the existing design (40). Moreover, from the lightweight point of view, if it reduces the thickness of the sheet, the score is 25 for both the alternatives and 15 for the existing design, which means that the existing design is much heavier as compared to the proposed or the new design. Subsequently, the existing design has a sheet thickness of 18 gauge, while the proposed design has two alternatives, i.e. 20 gauge (score 20) and 21 gauge (score 25) therefore alternative-II may be lighter in weight. Similarly, from a toughness point of view the existing score is 3 and it has 4 for alternative-I and alternative-II. From an aesthetics point of view, there has been no change in the aesthetics score, which remains the same. Therefore, from the lightweight point of view, it can be found that alternative two is scoring high.

Table 5.7 Evaluation matrix for existing and proposed parts/processes

Parameters weights alternative	Hardness		Lightweight		Toughness		Aesthetics		Total
	10		5		1		1		
Existing	4		3		3		3		61
		40		15		3		3	
Alternative - I	4		4		4		3		67
		40		20		4		3	
Alternative - II	5		5		4		3		82

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	50	25	4	3

Step 5: Presentation phase

The presentation phase is also called the recommendation phase. In this phase, the cost comparison is also made. Therefore, from a cost comparison point of view, there have been nine parts/processes. The cost of the existing design is 2380.00 ₹, however, the cost of alternative-I is 2050.00 ₹, which comes after reducing the thickness of the raw material, i.e., sheet from 18 gauge to 20 gauge and reducing the length of barrel from 1330 mm to 1220 mm with a marginal reduction in volume. Similarly, the cost of alternative-II is 1811 ₹, which comes after changing the material of the sheet from CR steel to DOS-A steel and the gauge thickness from 18 gauge to 21 gauge and length of barrel from 1330 mm to 1220 mm. As a result, alternative-II may provide a cheaper product without compromising performance or quality control, as well as a lightweight product. Therefore, it may be possible for a design engineer or customer to select alternative II. It would like to redesign the product in such a way that the cost is reduced without compromising the performance of the product, i.e. the basic essence of VE for all problems all across and all around the globe. If it utilizes this concept, it can achieve the functions but at a relatively lower cost without compromising the performance and reliability or other parameters, which are the quality characteristics of that product. Table 5.8 shows a cost-benefit matrix for the barrel.

Table 5.8 Cost-benefit matrix

S no.	Parameters	Existing Cost (₹)	Alternative-I Cost (₹)	Alternative-II Cost (₹)
1.	Raw material	1650.00	1320.00	1273.00

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2.	Seam welding	160.00	160.00	110.00
3.	Forming	100.00	100.00	100.00
4.	Assembly	60.00	60.00	60.00
5.	Pre-treatment	80.00	80.00	00
6.	Seaming	60.00	60.00	60.00
7.	Painting	80.00	80.00	68.00
8.	Baking	110.00	110.00	45.00
9.	Filling of packing	80.00	80.00	80.00
	Total	2380.00	2050.00	1811.00

Step 6: Implementation phase

Now implement the samples as per alternative-I and alternative-II, which have been manufactured and tested with the customer reports. Once the reports were found to be satisfactory for both the alternative-I and alternative-II, i.e. weight reduction was found and cost reduction. The proposal was put to the management and finance department for approval. Therefore, it always redesigns the product and saves money for the organization, i.e. the basic concept of VE. The samples as per alternative-I and alternative-II are manufactured and tested with the customer.

- Reports were found to be satisfactory for both alternatives.
- Weight, CO2 emissions, and power consumption are reduced with cost reduction in alternatives-I and alternative-II.
- The proposal was put up to the management/finance department for approval.

Step 7: Results and future scope

VE was used for cost reduction without changing the product design and its value. In this study,

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some changes have been made to the material. The overall design more or less remains the same: total savings incurred per product by implementing the above recommendations are 13.86% for alternative-I and 23.91% for alternative-II. Therefore, more cost-saving in alternative-II, which is lighter in weight. As a result, efforts have been made to redesign the barrel in such a way that it makes use of available alternatives without sacrificing its hardness, lightweight, toughness, and aesthetics. However, the weight is definitely reduced. Also, CO_2 is the most significant contributor to manufacturing emissions (energy usage and IPPU), representing a share of 98% of total emissions. The other greenhouse gases include CH4 and N2O.

In future, barrel product designs can be modified so that the value of the product can be enhanced. Other industrial engineering techniques can be used for further improvement of the product or process. This is not the only technique that will help us improve the performance of this particular product or process. Some other techniques are also available to improve the performance of the product. The study also helps in developing the needs of VE for circularity in the present manufacturing organization. Further, product development processes may be improved using CE and VE, which increase the effectiveness and ethical business objectives of the manufacturing process. Once the workers adopt a circular perspective, the organization will begin to gain additional benefits in terms of sustainable development.

5.5 Results and Discussion

In this study, VE and CE concepts are utilized to analyze the barrel manufacturing organization by reducing the CO_2 emissions, power consumption, material waste and overall cost of the barrel without compromising the performance of the product. In addition, CE execution in the product development process indicates resource conservation, ecological superiority, social

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equality, and economic prosperity (Ellen MacArthur Foundation, 2013). According to Setti et al. (2021), VE implementation is essential to minimizing manufacturing costs, which is crucial to the product's long-term sustainability. Nascimento et al. (2019) established the integration of CE and sustainable development and proposed a circular business model that redesign or recycle waste products such as electronic equipment. To achieve the research objectives, the study suggested a new material (DOS-A steel instead of CR steel) for the barrel in place of the existing one, which reduces the weight and cost of the manufacturing processes. Further, a decision matrix is developed to select the optimum alternative from the available alternatives found during the case study. Finally, the study revealed a substantial cost-reducing opportunity for an alternative–I is around 13.86% and for alternative-II is around 23.91%. Several tangible and intangible benefits have been observed during the case study, which is summarized as follows:

- The rate of production of barrels increases from 40 to 50 by selecting alternative-I and from alternative-II, it increases from 40 to 55. Similarly, the existing cost of one barrel was 2380 ₹ which may be reduced to 2050 ₹ by selecting alternative-I and 1811 ₹ by selecting alternative-II. Also, by implementing a new machine, the rate of production per day increases from 160 barrels to 400 barrels.
- The existing weight of each barrel was 22±0.5 kg, which can be reduced to 18±0.5 kg by selecting alternative–I (weight saving 4±0.5 kg) and by selecting alternative-II, it may be reduced around 17±0.5 kg (weight saving 5±0.5 kg).
- The amount of CO_2 emissions reduced by implementing PNG for the baking process is around 225.91 Ton per year. Also, the organization has the cumulative capacity to offset around 1825.91 tons of CO_2 each year by implementing cold-forming operations.

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- The amount of power saved by implementing a new machine for seaming processes is around 100 KVA.
- Changing the type of paint from normal paint to PBSA paint may increase the production of the barrel from 5 barrels/litre to 7 barrels/litre.
- By installing a 230 KWp grid-tied solar generation system, the organization may generate 224021 units of electricity (which is equivalent to ₹ 22.73 Lacs), which may reduce the total energy requirement by 25%.
- By implementing the effluent treatment plant (ETP) process, water wastage can be limited to 4%, and 90% of water may be further utilized for horticulture and green belt irrigation. The remaining 6% of treated water can be used for sludge output generation in solid form.
- 4.44 kg of material is wasted per MT of CR steel. These waste pieces of raw material may be further utilized in the production of key locks and bicycle bells.
- Organizations may provide regular skill development training and awareness programs to sensitize employees in the areas of CSR and sustainable development. The long-term CSR and sustainable development initiatives have been intended to minimize the carbon footprint.

5.6 Concluding Remarks

The manufacturing sector in developing countries like India is growing fast along with the global manufacturing industry. The products generated by the manufacturing industry have a wide range and at the end of the product life cycle, it generates a large amount of waste. Globally 2.01 billion tons of hazardous waste are generated annually and CO_2 emissions from

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manufacturing industries were around 26.40% in 2014. In barrel manufacturing, various products are wasted in the form of scrap, which does not contribute any value to the productivity of an organization. The VE methodology is a resilient tool for resolving organizational issues and improving the performance of products, processes and services. Further, by implementing CE principles (reduce, reuse and recycle) in the organization, the chances of wastage can be minimized. CE approaches are also helpful in the product development process. The implementation of CE in the product development has reduced the power consumption, CO_2 emissions and wastage of materials and moved us towards the sustainable development. It begins with the product development process and improves circularity by redesigning products throughout the product development process. As a result, the manufacturers continuously optimize both product and production performance, which may result in a more efficient use of resources. Therefore, CE and its sub-approaches have a lot of potential for improving manufacturing competitiveness. In the CE stage, VE focuses on the study of alternative resources, manufacture techniques, assembly-line methods and product life cost analysis, which may be helpful in cost reduction without compromising the performance of the product. It is widely considered a useful method for enhancing project performance and/or lowering wasteful costs and operational expenses. The significant contribution of this study is to reduce the total cost of the production, resource consumption, and environmental degradation in a manufacturing organization using the principles of VE and CE to achieve the triple bottom line performance. The results show that the total product development cost was reduced by 23.91%, and productivity of barrels per day increased by 150%, which enhanced the economic performance. Similarly, power consumption was reduced by 100 KVA, CO2 emissions by 1825.91 tons per year, water consumption by 96% and the total electricity requirement by 25%, which increased the environmental performance. Finally,

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the social performance of the organization increased by conducting skill development training and awareness programs, long-term CSR activities and sustainable development initiatives.

5.6.1 Limitations

The present study has limitations, including the fact that only triple bottom line aspect of the CE has been measured for the research work. In future studies, other performance parameters such as customer satisfaction and CSR may also be examined in depth. Moreover, there is an opportunity to examine the integration between individual decision strategies and sustainable performance in the future. This research was limited to Indian manufacturing organizations however, in future equivalent studies can be conducted in different industries in different countries. Furthermore, combining VE implementation with Industry 4.0-based technologies can be beneficial for long-term performance in the future industry. These technologies can provide real-time tracking on the product development processes and identify failures and errors, which may help to reduce breakdowns in the production processes.

5.6.2 Research implications

The finding of the study may be useful for researchers and industrialists in implementing VE and CE concepts in each stage of product development, including inception, manufacturing, bidding and product implementation. The VE methodology may also offer real cost reduction opportunities and improve the functional efficiency of the product through the selection of material, machinery and manpower. Further, it may be useful to provide alternative designs or technologies for the manufacturing of products that are cost-effective, lightweight, and durable without compromising the quality, while also promoting a triple bottom line of sustainability.

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Chapter 6

Identification and Prioritization of Implementation Factors for Industry 4.0 and Circular Economy

6.1 Introduction

The present research work aims to identify implementation challenges of Industry 4.0 and CE during a pandemic to achieve sustainable development goals. Based on a literature review and experts opinions, combined challenges of implementing Industry 4.0 for developing a circular supply chain were identified. A combination of ANP and Fuzzy TOPSIS approach has been selected for the proposed research because a network model with dependence and feedback improves the rankings derived from decisions. The ANP approach has been utilized to evaluate the weights of the criteria using Super Decisions software 2.10 version for reliability and accuracy of the results, while Fuzzy TOPSIS approach has been used to prioritize the alternatives.

6.2 Identification of Challenges for Industry 4.0 and CE Implementation

In the current manufacturing environment of CSC, industries need to use the emerging technology of Industry 4.0 for product monitoring, component failure and error and reverse logistic processes, which may help waste recovery and maintain product value chains. There are a number of factors that contribute that can serve as a foundation for discussion with an Indian manufacturing industry expert. A comprehensive literature review has been performed to identify the major challenges and applications of Industry 4.0 on CE. Moktadir et al. (2018b) found a lack of technological standards, which is the most prominent challenge of Industry 4.0 in the leather industry. Further, Kumar et al. (2020a) applied the DEMATEL approach and suggested that a lack of enthusiasm from the customers is the leading challenge of Industry 4.0

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in Indian SMEs. Rajput and Singh (2019b) used ISM hierarchical model and suggested that process digitalization and semantic interoperability are the prominent challenges of Industry 4.0 and CE. Moreover, Ozkan-Ozen et al. (2020) applied Fuzzy-ANP approach to prioritize the synchronized barriers of Industry 4.0 and CE. Abdul-Hamid et al. (2020) used the fuzzy Delphi approach to identify the most suitable barriers to the palm oil industry in Malaysia. Further, lack of experience to lead digitalization transformations, lack of effective reverse logistic system, lack of cooperation with supply chain partners, lack of environmental guidelines and standards and minimal engagement of top management towards sustainable development are the other major challenges for achieving a sustainable supply chain (Tseng et al., 2018, Dev et al., 2020, Sahu et al., 2022).

The combined challenges of Industry 4.0 and CE are explored from the detailed literature review, which is shown in Table 6.1. Five major challenges and fifteen criteria were identified from barrel manufacturing organization. Furthermore, the effect of these challenges and criteria are described comprehensively in this Table 6.1.

Table 6.1 Key challenges of Industry 4.0 and CE

Challenges	Criteria	Descriptions	Authors
Technological	Technological development	Lack of IT infrastructure, lack of communication channel, lack of scalability, high initial and disposal cost, insufficient network facilities, inadequate recycling technologies, and lack of resources for R&D that need to address and facilitate digital manufacturing, which supports to minimize resource extraction, unproductive methods, and CO_2 emission.	De Sousa Jabbour et al. (2018); Moktadir et al. (2018b); Dev et al. (2020); Mastos et al. (2021)
	Complexity in collaboration	Lack of skillset, lack of awareness, and lack of collaboration and data sharing procedure, and limited	Lu (2017); Walmsley et al.

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		knowledge about the Industry 4.0 technologies may create complexity within an organization to develop new products and existing systems.	(2019); Rajput and Singh (2019a); Khan et al. (2021a)
	Data security and privacy	Data transparency, data theft and lack of data management issues are present in the existing system. Therefore, it is challenging to develop silos to protect computer data and precarious design information from the unauthorized access and cyberattack.	da Silva et al. (2020); Abdul-Hamid et al. (2020)
Operational	Data management	Lack of data analysis, data mining and cleansing, data and information sharing, lack of effective reverse logistic system, quality compromise of the secondary material and product technology improvement.	Gölzer et al. (2015); Radanliev et al. (2018); Kumar et al. (2020a)
	Big data and analytics	Data integration complexity, higher data growth, lack of data analytics, insufficient data acquisition and recording system are the most major barriers of the CE implementation.	Sivarajah et al., (2017); Soualhia et al. (2017); Tseng et al. (2018)
	Strategic development	Lack of operational strategies for sustainable supply chain, traditional rules and regulations, poor leadership and management, poor R&D on Industry 4.0 and CE implementation, lack of adequate government planning and support for implementing Industry 4.0 and sustainable environment.	Schneider (2018); Luthra and Mangla (2018)
Organizational	Employment disruption	Implementing emerging technologies in manufacturing increases unemployment and fear of disruption to the existing job by replacing the workforce with machines.	Ghobakhloo (2018); Abdul-Hamid et al. (2020)
	Collaborative	Poor organizational culture, lack of collaboration and	Kamble et al.

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	model	coordination with supply chain partners, lack of human and machine interaction, and lack of social and ethical policies.	(2018a); Tam et al. (2019); Rajput and Singh (2019a)
	Decision-making ability	The complex and uncertain nature of CE needs high decision-making ability to integrate with a smart production system that manages resources sustainably and self-determination, social, and skilled workforce capabilities.	Gómez et al. (2018); Luthra and Mangla (2018); Raj et al. (2020)
Managerial	Management support	Anticipating market demand, lack of top management and stakeholder's support, conservative attitude of existing workers, lack of availability of skilled workers, and lack of expertise to lead digitalization initiatives.	Mangla et al. (2018); Saroha et al. (2018)
	Analysis and strategy	Lack of planning and implementation, ineffective take-back mechanism, lack of information management system, lack of risk management infrastructure, lack of availability of recycling/reuse products and lack of circular design.	Schneider (2018); Centobelli et al. (2020); Sahu et al. (2022)
	Human resource	Lack of competencies and abilities, lack of skilled workers and safety facilities for sustainable operation, lack of attention towards legal and ethical issues.	Schneider (2018); Saroha et al. (2018)
Sustainability	Social	The minimal involvement of top management authorities and competitive pressure towards the implementation of sustainable development leads to failures and non-consideration of social implications.	Kumar et al. (2020a); Yadav et al. (2020); Khan et al. (2021a)
	Economic	Lack of financial and economic feasibility, lack of economic inducement and fear of low economic returns are the major economic factors.	Kirchherr et al. (2017); Singh et al. (2020)
	Environmental	Lack of product and process design for sustainable	Sevigné-itoiz

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	supply chain, lack of environmental rules and regulations and massive automation that produces adverse impacts on the environment, which include huge power expenditure, depletion of natural resources, CO2 emission, and e-waste generation.	et al. (2014); Mangla et al. (2018); Walmsley et al. (2019); Karmaker et al. (2021)

6.3 ANP Fuzzy-TOPSIS Methodology

The selection of the implementation challenges of Industry 4.0 and CE depends on the various criteria and sub-criteria. Several MCDM approaches such as AHP, Delphi, DEMATEL, and fuzzy TOPSIS are available to address such problems. If the parameters are independent, TOPSIS and AHP are used, which is not the case in the presented problem. When using the AHP approach, it is assumed that the criteria are independent of one another, which is not feasible in real-life applications. Similarly, ANP has some advantages and disadvantages. According to Saaty (1996), ANP approach provides a hierarchical relation between criteria and sub-criteria and decision-making with feedback and dependence. As a result, a combination of ANP and Fuzzy TOPSIS multi-criteria approaches have been used for estimating the weights of the criteria and raking of the alternative, respectively. The following research path taken in this study is shown in Figure 6.1. The step-by-step procedure of research methodology is explained as follows.

Step 1: Identify the implementation challenges of Industry 4.0 and CE.

Step 2: Identifying the criteria and alternatives for decision-making.

Step 3: Select the MCDM approach and linguistic variables.

Step 4: Develop a pairwise comparison matrix using geometric mean.

Step 5: Develop an inner dependence matrix of evaluation criteria.

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Step 6: Develop a combined fuzzy decision matrix using Eq. (5), Eq. (6) and Eq. (7), respectively.

Step 7: Check the consistency through consistency ratio. If the value of consistency ratio (CR) is less than 0.1, then the matrix is acceptable, while if the value of CR is more than 0.1, inconsistency may occur (Gogus and Boucher 1998, Rekik et al., 2016). In this case, the judgment process should be revised.

Step 8: Calculate the criteria weights using ANP approach. The criteria weights are ranked by the highest value of crisp weight.

Step 9: Select the best alternatives using a combined fuzzy decision matrix.

Step 10: Develop a fuzzy normalized decision matrix and weighted fuzzy normalized matrix.

Step 11: Evaluate fuzzy positive/negative ideal solution.

Step 12: Finally, rank the alternatives using the fuzzy TOPSIS approach. Ranking the alternatives is chosen by the highest value of closeness coefficient (CC_i) or the descending order of CCi.

6.3.1 Analytic network process

ANP is one of the most commonly used MCDM approaches, which is the extension of AHP (Ozkan-Ozen et al., 2020). According to Saaty (1996), ANP approach has replaced the hierarchies of AHP approach with the network. Further, it is used to estimate all inner and outer dependence criteria and feedback in decision-making problems. As per the existing literature, AHP, ANP, DEMATEL, PROMETHEE and ELECTRE are among the most widely used MCDM techniques for Industry 4.0 and CE challenges. The ANP provides its own set of benefits and has developed excellent results in a variety of disciplines. In the study, ANP approach has been utilized to evaluate the criteria weight of the Industry 4.0 and CE challenges for selecting the best alternatives. The following notation of criteria are used C1: Technological development, C2: Complexity in collaboration, C3: Data security and privacy, C4: Data

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management, C5: Big data and analytics, C6: Strategic development, C7: Employment disruption, C8: Collaborative model, C9: Decision-making ability, C10: Management support, C11: Analysis and strategy C12: Human resource, C13: Social, C14: Economic, C15: Environment. Additionally, alternatives used are denoted by the notation A1: Technological, A2: Operational, A3: Organizational, A4: Managerial, A5: Sustainability. The stepwise procedure of ANP approach by utilizing the geometric mean technique is described in the following sub-section.

Sub-step 1. Construct a model and structure the problem. The ANP approach has three components: (i) the objective of selecting the best alternative, (ii) the model's criteria and sub-criteria, and (iii) the alternatives. Dimensions and attribute enablers are the two types of elements in the hierarchy of determinants. The construction of a decision model requires the identification of dimensions and variable enablers at each level and development of the relationship between them. The key objective of the hierarchy structure is to prioritize the alternatives (Morteza et al., 2016).

Sub-step 2. Develop a pairwise comparison matrix (A) and local priority vector. The pairwise comparison matrix is constructed using a nine-point preference scale, as shown in Table 6.1.

Each element aij (i, j = 1, 2,..., n) in the judgement matrix A, is the proportion of weights of the criteria as presented below:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{12} & \dots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{21} & \cdots & a_{22} & \dots & a_{2n} \\ \vdots & & \vdots & & \vdots \\ a_{31} & \cdots & a_{32} & \dots & a_{3n} \end{bmatrix}, \quad a_{ii} = 1, a_{ij} = \frac{1}{a_{ij}}, a_{ij} \neq 0 \qquad (1)$$

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Sub-step 3. The weights of the criteria are estimated based on the limited supermatrix using Super Decision software. In the last step, obtained criteria weights are approved by a group of experts.

Sub-step 4. Check the consistency through a pairwise comparison matrix. In case of triangular fuzzy number, the consistency check through the largest Eigenvalue (λ_{max}).

The CR value is calculated by applying the following relation:

Consistency ratio (CR) = $\frac{CI}{\text{RI corresponding to n}}$ (2)

Where, CI is the consistency index that can be estimated through the following relation:

Consistency index (CI) = $\frac{(\lambda_{max} - n)}{(n-1)}$ (3)

Further, random index (RI) may be obtained through Table A.2 (Appendix A).

Sub-step 5. Selection of important alternatives.

6.3.2 Fuzzy TOPSIS

The TOPSIS approach was initially implemented by Chen and Hwang (1992), concerning to Hwang and Yoon (1981). This approach is founded on the notion that the selected alternative should have the shortest geometric distance from the positive ideal solution that minimizes the cost and maximizes the benefit and extreme distance from the negative ideal solution. Moreover, the existing TOPSIS approach implies that criteria weights and rankings are in a crisp number that is not adequate in the real-time situation. To overcome these situations, the fuzzy set theory was introduced (Xu and Chen, 2007). Zadeh (1976) introduced the fuzzy set theory into the TOPSIS for dealing with uncertainty and vagueness of the human's decisions. The Fuzzy TOPSIS approach, a five-point linguistic scale was used to rank the alternatives and

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criteria weights, sub-criteria, and alternatives. The following sub-steps are used in the fuzzy TOPSIS method.

Sub-step 1: Choose the best alternatives for identifying the decision matrix using linguistic terms based on the expert respondent. The five-point scale has linguistic terms Little Importance (LI), Important (I), Absolute Important (AI), Moderately Important (MI), and Very Important (VI), as shown in Table A.3 (Appendix A).

C_1 A_1 A_n

$$D = \vdots \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (4)$$

C_m

Sub-step 2: Evaluate combined fuzzy decision matrix x_{ij} through Eq. (5), Eq. (6), and Eq. (7).

$x_{ij} = (a_{ij}, b_{ij}, c_{ij})$

$$\text{Where, } a_{ij} = \frac{\min}{k} \left\{a_{ij}^{k}\right\} \quad (5)$$

$$b_{ij} = \frac{1}{k} \sum_{k=1}^{k} \frac{{b_{ij}}^{k}}{k} \quad (6)$$

$$C_{ij} = \max \left\{C_{ij}\right\} \quad (7)$$

Where, k is the decision-maker number and x_{ij} is fuzzy opinion.

Sub-step 3: Constructed fuzzy normalized decision matrix $[r_{ij}]_{m\times n}$ through vector normalization technique for the beneficial criteria (see Eq. 8).

$$r_{ij} = \frac{x_{ij}}{(\sum_{i=1}^{m} x_{ij}^{2})^{1/2}} \quad (8)$$

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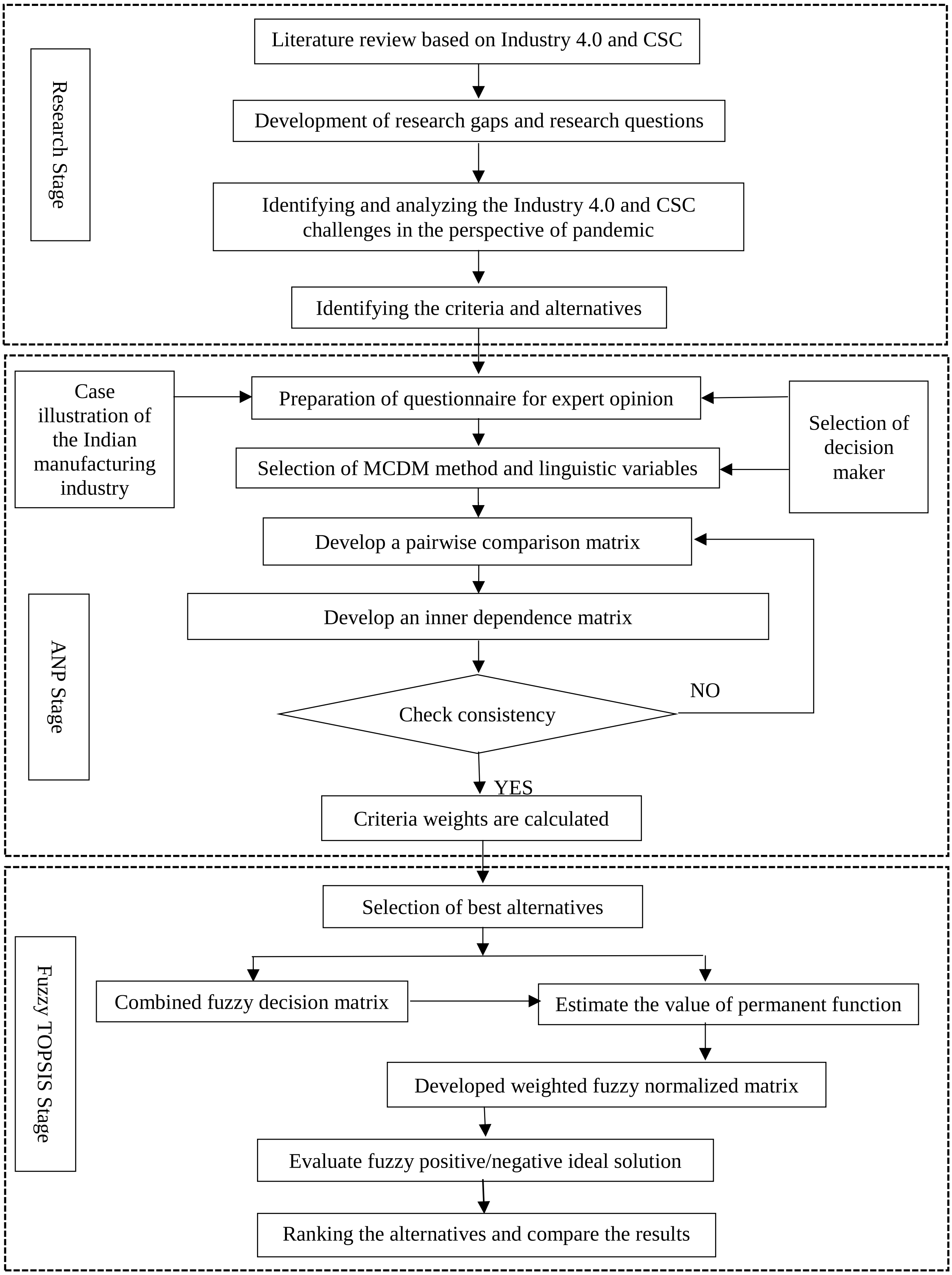

Figure 6.1 Research path of the present study

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Where, i = 1, . . . , m and j = 1, . . . , n.

Sub-step 4: Evaluate weighted fuzzy normalized decision matrix $[v_{ij}]_{m\times n}$ through Eq. (9).

$$\widetilde{V_{IJ}} = \widetilde{r_{IJ}}\times\widetilde{w_J},\ i \in [1, m] \text{ and } j \in [1, n] \qquad (9)$$

Where, wj (j∈n) is the weight of j^{th} criteria or attribute.

Sub-step 5: Evaluation of the fuzzy positive ideal solution (FPIS, A^+) and fuzzy negative ideal solution (FNIS, A^-).

$$A^+ = \{\widetilde{V1}^*, \widetilde{V2}^*, \ldots\ldots \widetilde{Vn}^*\}, \text{ where } \tilde{V}_J^* = \max_i \{V_{ij3}\} \qquad (10)$$

$$A^- = \{\widetilde{V1}^-, \widetilde{V2}^-, \ldots\ldots V_n^-\}, \text{ where } \tilde{V}_J^- = \min_i \{V_{ij1}\} \qquad (11)$$

Sub-step 6: Evaluation of the sum of distance (D_i^+ and D_i^-) from a positive and negative ideal solution respectively for each alternative using the vertex method (See Eq. (12) and Eq. (13)).

$$D_i^+ = \sum_{j=1}^{n}(Vij - Vij^*),\ i \in [1, m] \qquad (12)$$

$$D_i^- = \sum_{j=1}^{n}(Vij - Vij^-),\ i \in [1, m] \qquad (13)$$

The distance between two triangular fuzzy numbers is evaluated through vector algebra $d(\tilde{a}, \tilde{b})$ defined by Eq. (14). Where a = (a_1, a_2, a_3) and b = (b_1, b_2, b_3).

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \qquad (14)$$

Sub-step 7: Evaluate the value of closeness coefficient (CC_i) of each alternative to the ideal solution. The CC_i value is evaluated using Eq. (15) to determine the rank of each alternative. Further, the CCi

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value with respect to A^+ is expressed as:

$$\text{Closeness coefficient } (CC_i) = \frac{D_i^-}{D_i^- + D_i^+}, \qquad i = 1, 2, \ldots, m \qquad (15)$$

Sub-step 8: Ranking the alternatives based on the highest value of CCi.

6.4 Case study of the ANP Fuzzy-TOPSIS Approach

The challenges in the implementation of Industry 4.0 and CE in barrel manufacturing have been prioritized using the ANP fuzzy-TOPSIS approach. Four experts of the barrel manufacturing organization were considered for decision-making of various criteria and sub-criteria. The organization profile is demonstrated as follows.

6.4.1 Organization profile

A barrel manufacturing organization XYZ has been selected to illustrate the proposed methodology. The present organization is selected because of the largest manufacturer of steel barrels in developing countries like India. XYZ is a market leader in steel barrels manufacturing with a total 45% market camp. The organization has an annual turnover is more than 500 Million INR. The organization has a primary objective to become a leading industry in Asia and placed among the top ten organizations in the global market for manufacturing steel barrels. Further, the organization has always emphasized R&D in order to develop environmentally friendly and biodegradable products and implement zero waste in their production environment. According to figures released by the human resource department, the current demand for barrel products will expand by up to 35 percent over the next two decades. The manufacturing unit of this organization was established in the early period of the twentieth century, and approximately 10,000 employees are working in this organization. The organization has manufacturing, technology, finance, logistics, and service divisions are

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established in the four quadrilateral of India, including Delhi, Mumbai, Kolkata, Chennai, etc. The organization has mainly centered on lean manufacturing, continuous improvement, green culture, and waste reduction. Currently, the organization has major challenges in the implementation of Industry 4.0 and CE in its manufacturing division.

The study identifies and analyzes the most influencing challenges in the steel barrels manufacturing organization to implement Industry 4.0 applications for the continuous and large-scale waste retrieval of barrel trash. The four experts from the organization were selected to review the preliminary draft of the questionnaire. These experts were asked to discuss the multiple objectives and decisions that chose the critical challenge in this research. For the XYZ organization, the first decision-maker is an operations manager who has ten years of experience. The second decision-maker is a production engineer with twelve years of experience, and the third decision-maker is a supply chain manager who has fifteen years of experience. Finally, the fourth decision-maker is a plant head of the selected organization having sixteen years of industrial experience. The questionnaire was developed to evaluate the essential criteria. The criteria were analyzed and rated in decision-making processes, and the findings were presented from the investor's perspective. The questionnaire is developed in Table B.1 (Appendix B). The following steps were taken to develop an Industry 4.0 and CE decision-making model.

6.5 Results and Discussion

The main purpose of the study is to identify the implementation challenges of Industry 4.0 and CE on sustainable development in the Indian manufacturing organization. The proposed findings help to find a more extensive understanding of the consequence of Industry 4.0 technologies on CE for long-term growth. Prior research like Ozkan-Ozen et al. (2020), has developed a correlation among the implementation of Industry 4.0 technology and CE for the

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long-term success of businesses. Furthermore, Li et al. (2020) suggested that manufacturing industries should implement Industry 4.0 technologies to improve their financial, social and environmental performance. The combination of ANP and Fuzzy TOPSIS approaches has prioritized the current manufacturing challenges of the pandemic. To prioritize the alternatives of Industry 4.0 and CE, five challenging factors were identified and considered in this study. These factors are technological, operational, organizational, managerial, and sustainability. Additionally, these factors were prioritized on the basis of beneficial criteria.

Table 6.2 Combined fuzzy decision matrix

	A1: Technological	A2: Operational	A3: Organizational	A4: Managerial	A5: Sustainability
C1	(6, 8.5, 10)	(4, 6 ,8)	(6, 7.5, 10)	(2, 4, 6)	(6, 8, 10)
C3	(6, 8, 10)	(4, 6, 10)	(2, 3.5, 6)	(4, 5.5, 8)	(2, 4.5, 6)
C5	(1, 6, 10)	(6, 8, 10)	(4, 6, 8)	(6, 8, 10)	(4, 6.5, 8)
C9	(2, 4, 6)	(4, 6, 8)	(2, 4.5, 8)	(2, 7, 10)	(4, 5.5, 8)
C10	(1, 2, 4)	(2, 4, 6)	(2, 5, 8)	(6, 8.5, 10)	(6, 8, 10)
C14	(4, 7.5, 10)	(6, 8.5, 10)	(6, 8, 10)	(6, 8, 10)	(6, 8, 10)

Table 6.3 Fuzzy normalized matrix using vector normalization technique

	A1	A2	A3	A4	A5
C1	(0.416, 0.589, 0.693)	(0.371, 0.557, 0.743)	(0.433, 0.541, 0.721)	(0.267, 0.535, 0.802)	(0.424, 0.566, 0.707)
C3	(0.424, 0.566, 0.707)	(0.324, 0.487, 0.811)	(0.277, 0.484, 0.830)	(0.381, 0.524, 0.762)	(0.258, 0.580, 0.773)
C5	(0.085, 0.513, 0.854)	(0.424, 0.566, 0.707)	(0.371, 0.557, 0.743)	(0.424, 0.566, 0.707)	(0.362, 0.588, 0.724)
C9	(0.267, 0.535, 0.802)	(0.371, 0.557, 0.743)	(0.213, 0.479, 0.852)	(0.162, 0.566, 0.808)	(0.381, 0.524, 0.762)
C10	(0.218, 0.436,	(0.267, 0.535,	(0.207, 0.518,	(0.416, 0.589, 0.693)	(0.424, 0.566, 0.707)

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	0.873)	0.802)	0.830)		
C14	(0.305, 0.571, 0.762)	(0.416, 0.589, 0.693)	(0.424, 0.566, 0.707)	(0.424, 0.566, 0.707)	(0.424, 0.566, 0.707)

Table 6.4 Normalized weighted fuzzy decision matrix

	A1	A2	A3	A4	A5	(FPIS, A*)	(FNIS, A-)
C1	(0.086, 0.121, 0.143)	(0.076, 0.115, 0.153)	(0.089, 0.111, 0.149)	(0.055, 0.110, 0.165)	(0.087, 0.117, 0.146)	(0.055, 0.110, 0.165)	(0.055, 0.110, 0.165)
C3	(0.128, 0.170, 0.213)	(0.098, 0.147, 0.244)	(0.083, 0.146, 0.250)	(0.115, 0.158, 0.229)	(0.078, 0.175, 0.233)	(0.083, 0.146, 0.250)	(0.078, 0.175, 0.233)
C5	(0.016, 0.095, 0.158)	(0.078, 0.105, 0.131)	(0.069, 0.103, 0.137)	(0.078, 0.105, 0.131)	(0.067, 0.109, 0.134)	(0.016, 0.095, 0.158)	(0.016, 0.095, 0.158)
C9	(0.035, 0.071, 0.106)	(0.049, 0.074, 0.098)	(0.028, 0.063, 0.112)	(0.021, 0.075, 0.107)	(0.050, 0.069, 0.101)	(0.028, 0.063, 0.112)	(0.021, 0.075, 0.107)
C10	(0.017, 0.033, 0.066)	(0.020, 0.041, 0.061)	(0.016, 0.039, 0.063)	(0.032, 0.045, 0.053)	(0.032, 0.043, 0.054)	(0.017, 0.033, 0.066)	(0.016, 0.039, 0.063)
C14	(0.030, 0.057, 0.076)	(0.042, 0.059, 0.069)	(0.042, 0.057, 0.071)	(0.042, 0.057, 0.071)	(0.042, 0.057, 0.071)	(0.030, 0.057, 0.076)	(0.030, 0.057, 0.076)

The study is analyses that "Data security and privacy" (C3) and "Technological development" (C1) acquired the highest weightage criteria. Data security and privacy is found to be the most important criteria that highlight data transparency and privacy issues. It may be an important aspect to protecting databases and crucial product design or information from unauthorized access and cyberattacks. Consequently, the manufacturing organization should more focus on data security and privacy compared to other criteria. Technological development is the second important criteria found that includes the insufficient development of sensor technology, modern IT infrastructure and improper communication and network facilities that may be used to monitor and predict the product consumption pattern. Further, the use of latest

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technologies, including IoT, RFID, and EDI in CE may be useful to collect the waste product information through real-time product tracking and identify the failure and errors in the existing supply chain processes (Reyes et al., 2015) Moreover, the initial cost of adopting these technologies in present Indian manufacturing industry is challenging, however these technologies have capabilities to enhance the effectiveness and rate of the production process (Kumar et al., 2020a).

Table 6.5 Sum of the distances to ideal solution and final results

Alternatives	D_i^+	D_i^-	CC_i	Ranking position
A1	0.112	0.112	0.5	3rd
A2	0.092	0.102	0.526	2nd
A3	0.065	0.088	0.575	1st
A4	0.09	0.08	0.47	4th
A5	0.107	0.09	0.457	5th

The present study reveals that 'Organizational (A3)' is the highest-ranked challenge while implementing Industry 4.0 technologies on CE during the pandemic. Moreover, our findings reveal that 'Operational (A2)' and 'Technological (A1)' challenges have ranked in second and third position, respectively. The another challenges with the highest priority are 'Managerial (A4)' and 'Sustainability (A5)', challenges that manufacturing industries should initially implement. Luthra and Mangla (2018) identified that organizational challenge (A3) is one of the important characteristics in implementing the sustainability of supply chains within Industry 4.0 in the Indian manufacturing organization. Moreover, the sophisticated and vagueness environment of CE needs a high decision-making strategy and a smart manufacturing system that manages resources sustainably. The organizational dimension has the capability to develop a more resilient supply chain and decision-making strategies to

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address future challenges without disrupting sustainability.

'Operational (A2)' challenge obtains the next important priority level. Operational challenges consist of many factors such as data and information sharing, lack of data analytics in the supply chain, and lack of adequate government planning and support for implementing Industry 4.0 and a sustainable environment.

'Technological challenge (A1)' is the next important aspect of present manufacturing. The effect of technological challenges consists of many factors, including lack of IT infrastructure and internet facilities, lack of data sharing protocols and cloud network issues, and lack of transparency and privacy. The technological challenge is concerned with technology itself. It includes both internal and external technology in the organization, which affects the overall production rate. In the present Indian manufacturing industry, the technological challenge plays an important role to develop circular strategies and a sustainable environment. It includes the challenges of lack of information about the latest technology and automation, smart manufacturing systems, sourcing and retaining IT talent, and lack of resources for R&D. Hofmann and Rüsch (2017) stated that for successful Industry 4.0 implementation, Indian manufacturing industry must understand the economic opportunities of IoT. It can be understood as amongst the most promising technologies with massive potential implications.

'Managerial (A4)' challenge acquires the subsequent level of the priority list. Schneider (2018) suggested that management support provides the decision-making support and strategic transformation path for developing a new business model. The advancement of the present manufacturing industry may cause unemployment and fear of disruption from the existing jobs. Further, a lack of collaboration with supply chain partners and human-machine interaction may cause a delay in production and breakdown due to the unavailability of modern machine parts and maintenance skills.

'Sustainability (A5)' is considered the last most important challenge of the current manufacturing industries. In the present condition, sustainability plays a substantial character

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in strengthening the CE. It fulfills the various objectives of the supply chain, i.e., economic, environmental and social. Rajesh et al. (2020) suggested that sustainability is getting significant in the Indian manufacturing sectors, as there are growing considerations from stakeholders for resource consumption and reducing environmental degradations. According to Machado et al. (2020), organizations must consider socio-economic, environmental, legal, and human rights-related steps though developing their strategies for sustainable development. Additionally, a sustainable supply chain mitigates risks and uncertainties caused by pandemic, such as bottlenecks in the logistics process restricting the information flow, capital flow and visibility of the production. Consequently, business stability and distribution process improve, which can reduce production and delivery delays and cost.

6.6 Concluding Remarks

The present research work has identified and analyzed the effect of Industry 4.0 technologies on CE in the COVID-19 perspective. The pandemic considerably affects the global trade (including manufacturing sectors) of several developed and developing economies (Kumar et al., 2020b). Since most trade routes are disrupted or redirected due to this pandemic, the logistic process is directly affected by the supply and demand of the raw material. Therefore, it is necessary to adopt a sustainable and resilient logistic system that can resolve the uncertain business environment of the pandemic. The employment of Industry 4.0 technologies, including CPSs, IoT, Big Data, and Cloud Computing have capabilities to develop a decentralized manufacturing system. The study has analyzed the insight of the barrel manufacturing industry related to the influence of Industry 4.0 technologies on CE from the sustainability perspective. The developing economies like India in which a total of sixteen percentage contributions of GDP from the manufacturing sector (Kumar et al., 2020a). Moreover, manufacturing industries are the most important source of employment in India. Therefore, in this study, the consideration of the manufacturing industry is the prime focus.

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The literature review found that very limited studies have considered the application of Industry 4.0 technologies in CE implementation during the pandemic. However, these studies considering the combination of ANP and fuzzy TOPSIS for selecting combined challenges of Industry 4.0 and CE are rarely observed. Therefore, the authors analyzed the combined challenges of implementing Industry 4.0 and CE in the manufacturing organization during pandemic. To address the given organization problem, ANP approach has been utilized to find the relative weights of the criteria. Further, fuzzy TOPSIS approach has been used to prioritize the alternative challenges. In this study, two research questions were asked: To answer the first research question (Q1), five challenges and fifteen criteria that affected these challenges had been identified from the literature review. For the second research question (Q2), a combination of ANP and fuzzy TOPSIS approaches were used to prioritize these challenges. The study shows that data security and privacy, technological development and big data analytics are the essential criteria while implementing Industry 4.0 and CE concepts. Furthermore, organizational is the highest-ranked challenge in the considered organization, followed by operational, technological, managerial, and sustainability, which XYZ manufacturing organization should initially resolve.

6.6.1 Managerial implications

This study seeks to address the sustainability characteristics of manufacturing processes, especially their value chains, by using Industry 4.0 and CE to facilitate industries in such circumstances. The study discusses a statistical model and numerical findings to understand the pandemic effect better and formulate resilient and sustainable supply chain strategies. In such circumstances, managers and industrialists need to consider the sustainability perspective in manufacturing industries while adopting the modern technologies of Industry 4.0 and CE for sustainable development. Furthermore, Industry 4.0 and CE implementation are still in the primary stage of development.

Part of the chapter is published as:* "Challenges of Implementing Industry 4.0 in Achieving Sustainable Development Goals: A Case of Indian Manufacturing Organization", **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, Vol. In-Print, pp. In-Print.

The study will guide academic researchers and supply chain partners in decision-making to limit the disruption of the pandemic in developing economics. The main challenge that organizations need to focus on the sustainable development to manage the impact of pandemic. Adapting with challenges and developing valuable decision-making skills to make effective decisions are substantiated pathways for organizations looking to improve their environmental sustainability. The supply chain partners should pay more attention to these challenges during the implementation of CE in their organizations.

6.6.2 Limitations and future research directions

The number of experts considered in the analysis is limited. Therefore, when the vaccination of COVID-19 will completed, more responses from different industries could be collected. Further, this study has been considered only the Indian manufacturing sector; however, research could be applied to other developed and developing economies with marginal modifications. Therefore, as time passes, these analyses may consider the other sector such as healthcare, automobile, tyre recycling, food processing and textiles industries, etc. The authors have considered five challenges and fifteen criteria for implementing Industry 4.0 technologies during pandemic in order to develop a CE. Future researchers could explore other factors affecting this implementation, such as legal and ethical effects, human-machine collaboration, and sustainable effects, etc. In addition, the identified challenges can be investigated further in future research to determine their causal and dependent relations. The present study has used a combination of ANP and fuzzy TOPSIS approaches; as time passes, future research could be compared to these approaches with other MCDM approaches, which may suggest the best method to consider these factors. In future research, sensitivity analysis may also be conducted. Finally, organizations must design and develop circular business models to deal with managerial and environmental disruptions due to pandemic using Industry 4.0 applications (Centobelli et al., 2020).

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Chapter 7

Development of Framework for the Legal Issues in the Implementation of Industry 4.0

7.1 Introduction

The research work analyzed how legal tech Industry 4.0 technologies become an important part of legal informatics systems by providing real-time monitoring and streamlined and tailored services. In the current scenario of increasing digitalization, e-government, and e-commerce, managing LI for long-term performance has become a challenge. A contemporary development in e-government that has substantial implications for the legislative process is the document sharing and application interoperability between the court's internal users (judges, clerks, etc.) and all its external users (lawyers, eyewitness, etc.). The study investigates the impact of Industry 4.0 technologies that can provide decision-making support for lawyers. Also, Big Data and cloud computing technologies are more flexible, cost-effective and client-centric. The present study proposed a conceptual legal informatics framework to advance and improve the existing legal justice system. Additionally, the implementation of sustainable legal-tech in the legal domain makes the process more efficient, economically viable, and accessible to even the most marginalized members of society.

7.2 Execution of Industry 4.0 in Legal Informatics System

The study proposes a legal informatics system framework based on the extensive literature review. The purpose of this framework is to develop close connections between law and technology, i.e. e-Law. Figure 7.1 shows the framework for the legislature information system. This legal informatics system framework has six components, namely, legal tech Industry 4.0;

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IT law; governing bodies; LI implementation; legal and ethical issues; and process and control that are connected with and dependent on each other. Implementing Industry 4.0 technologies in the legal informatics system will provide advanced process control, interoperability, real-time monitoring, virtualization, and decentralization. Moreover, many legislative bodies already have extensive information systems in place to facilitate all major internal activities as well as connections towards the social and political environment.

7.2.1 Role of legal tech Industry 4.0 in legal informatics

Legal tech is a collection of software and other electronic resources that are aimed at streamlining and optimizing the judicial process. It is further providing technological solutions for legal professionals to enhance the performance of legal services. Industry 4.0 is the most revolutionary paradigm for most industries, it's not only affecting the total profitability and cost frameworks but also key business and operating methods. The application of AI in the legal justice system will have a remarkable effect when law firms understand all of the advantages that it will bring (Liao et al., 2017; Kamble et al., 2018a). Many industries have already implemented AI into their operational processes to streamline their activities while also substantially minimizing margins of error. For example, a UK government agency uses AI to allow civil litigation cases from road accidents to be handled virtually, thereby reducing costs and improving customer service. One more application may be targeted to the time-consuming task of analyzing contractual agreements to find terms for certain provisions. This is one of the most critical functions in the judicial decision, and it requires the most time and effort.

Moreover, employing machine learning algorithms and AI-based software can be used to identify and analyze the most important case information. This accelerates the process and allows lawyers to focus on activities that need more research, analysis, and experience.

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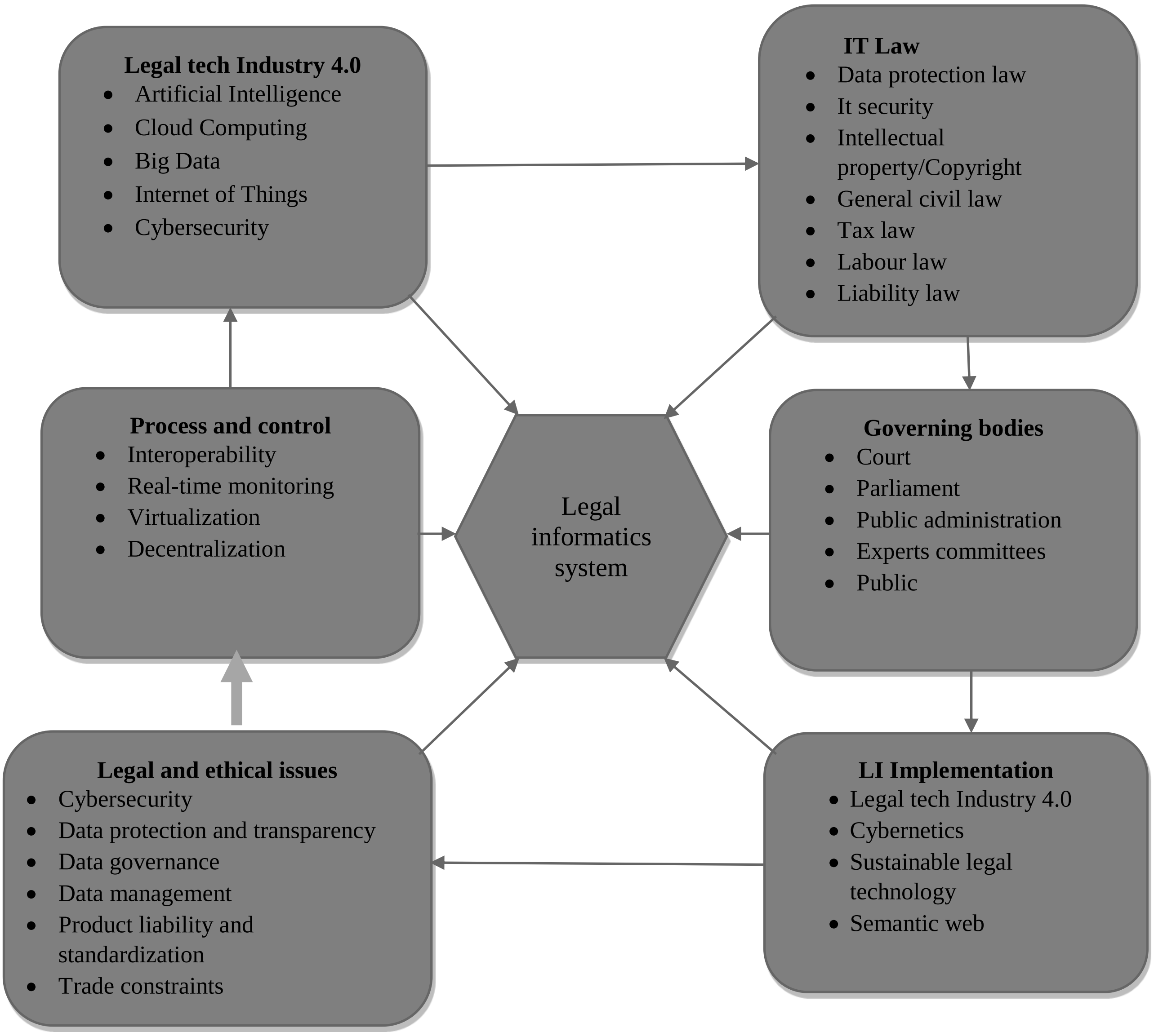

Figure 7.1 Framework for legal informatics system

The purpose of AI in the legal industry is to complement the work of lawyers rather than replace the activities of lawyers (Waltl et al., 2018). Consequently, the objective is to deliver necessary equipment to support their more repetitive activities so that they can have more time to perform specialized tasks. When lawyers provide their services through the cloud computing network, it can be more streamlined and tailored to their specific needs. Cloud-based case management services utilized by legal technology firms allow the client to track and monitor the progress of case negotiations on a real-time basis, similar to tracking a package and waiting for it to be

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delivered (Schmidt et al., 2015; Sharma et al., 2019). When the case is settled, these cloud platforms will safely keep the information, which is a possibly better alternative than placing a case in an office folder and storing it in an unknown area. Industries are expected to use Big Data to monitor and secure their raw data as well as gain a better understanding of their customers (Sivarajah et al., 2017; Frank et al., 2019). Industries may be required to anticipate potential safety and security risks with new products and technology as Big Data tools become more sophisticated and ubiquitous. In this sense, lawyers will need to comprehend organizational data and what can be learned from it in order to handle issues and limit legal risks.

7.2.2 Role of Information technology act, 2000 India in legal informatics system

Information technology law is a branch of law that investigates the legal implications of IT and seeks to resolve legal issues that arise due to its introduction and use in society. According to the law, a person can use a legal information retrieval system and digital access to legal documents such as case files, laws, judgments, and acts (Goswami et al., 2018). The Information technology act, 2000 may also help to develop a comprehensive computational system that can register complaints online without going in person to a police station. In addition, IT tools that provide data mining, data analytics and data visualization methods may help in studying simple to complex crime data in an efficient manner. Sharma et al. (2021) suggested some of the online search platforms available in India, such as Indian Kanoon, and Manupatra for accessing and retrieving legal documents.

Further, lawyers must have a basic understanding of these emerging technologies to comprehend their influence and develop the law most appropriately. AI and law are practically synonymous with each other that's why it's termed "Information Technology for Litigators". Study in AI and law is an essential aspect that focuses on modelling legal reasoning and legal

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decision-making. In addition, the Indian cyber legal justice system is regulated by Information Technology Act (ITA), which was implemented in 2000 (Sharma et al., 2021). The main aim of this Act is to deliver e-commerce with adequate legal protection by making it easier to register real-time information with the government. The ITA, which was established by India's Parliament, emphasizes the harsh fines and penalties that protect the e-governance, e-banking, and e-commerce sectors. The opportunity of ITA has now been expanded to include all of the most recent communication policies. This law also empowers the Indian government and technology and industrial corporations to share information about Internet traffic. Implications of Information Technology and law addressed an opportunity to reflect on indexing challenges connected to database providers' identifiers and characteristics (He et al., 2003). Figure 7.2 depicts the various field of law that affect Industry 4.0 technologies. It is evident from Figure 7.2 that the data protection law most strongly impacts on digitalization. Therefore, corporate lawyers must also pay attention to the contract, liability, and intellectual property law from the perspective of digitization. Tax law, labour law and competition law also appear to be essential but not urgent.

The development of information technology in society tends to create new situations and may need the revision of legal regulations and, in some cases, the design and development of new legal solutions. One recurring issue that has already been mentioned is the formation of terminology and conceptual frameworks. The task is far from elementary, and it might be considered part of a comprehensive LI methodology. Though implementing LI, one should be paid special attention to the following parameter.

- Adapting, developing, and integrating close legal and technical principles.
- Defining the IT environment in a way, i.e. legal.
- Overall frameworks and regularities are examined.
- The notion of 'viable steering models' is used to design legal regulations.

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The following changes may require in IT Act 2000 in the process of Industry 4.0 integration. Implementing advanced technologies of Industry 4.0 in the present legal system can develop a legal prediction model or prototype that may predict law decisions more accurately (Sharma et al., 2021). These systems may assist legal informatics for decision-making by providing a cost-effective and quicker decision-making process. Further, the implementation of electronic governance in the current legislation system may also be improved by incorporating legal recognition of electronic records as well as electronic signatures.

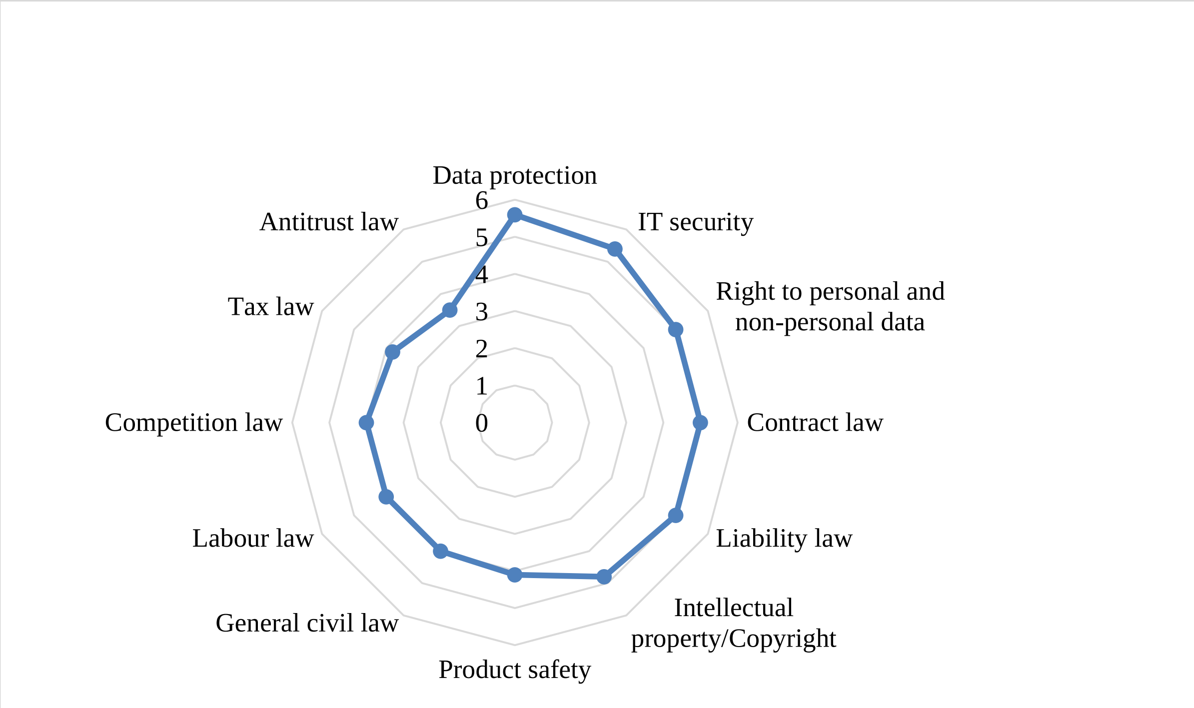

Figure 7.2 Field of law that affects Industry 4.0 technologies digitalization

7.2.3 Role of governing bodies in legal informatics

The legislative information system connects all the government bodies, including courts, parliament, public administration, experts committees, and public etc. As governing bodies become more sensitive when developing and executing specific LI laws and policies. It becomes more important to encourage good governance that utilizes emerging technologies of Industry

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4.0. As a step toward developing good governance in the legal domain with a long-term sustainability objective, this study provides a technology-based approach to collect and analyze public outreach and agreement on policies and procedures. Government authorities have adopted Industry 4.0 technologies as real-time e-communication and e-participation tools. Its enhanced transparency and accountability, global outreach, and cost-effective service make it a significant government indicator. Additionally, Industry 4.0 based initiatives that promote accountability and transparency of courts, parliament, public administration and people are essential for good legislative governance (Zhong et al., 2017).

7.2.4 Implementation of the legal informatics system

The application of emerging technology and massive digitalization has to create the requirement for a developed appropriate legal justice system that will fulfill the goal of LI. To achieve this goal, the present section discusses the various implementation possibilities such as legal tech Industry 4.0, cybernetics, semantic web and sustainable legal technologies.

7.2.4.1 Implementation of legal informatics through cybernetics

Cybernetics and its law play a significant character in strengthening legal informatics system. Cybernetics is defined as the study of "communication and control systems" applicable to both physical processes and living organisms in natural and artificial regions (Contissa et al., 2021). The word cybernetics refers to the utilization of information theory and technology to better understand how information affects the “control” of systems. This new cognitive approach and interpretative principle introduced by cybernetics will subsequently transform the social domain, including the legal sector, where Industry 4.0 implementation can monitor and control the processes (Zatarain et al., 2018). Further, cybernetics has various applications in legal justice systems such as legislative process, jurisdiction public administration and legal professional

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works.

The core principle of cybernetics is to develop the relationship between IT and law, which explains cybersecurity as “protecting information, technologies, hardware, software, computer device, communication asset, and data stored therein from unauthorized access, use, disclosure, interruption, alteration, or demolition (Biasiotti et al., 2008). The Information Technology Act, 2000 has established various rules thereunder to provide legal recognition and protection for transactions carried out through digital information and other means of electronic communication. It also focuses on information security and reasonable security policies for businesses to follow, redefines the character of intermediaries, and acknowledges the Indian Computer Emergency Response Team ("CERT-In"). Table 7.1 shows the IT act govern by Indian jurisprudence to regulate cybersecurity. These acts have been utilized for the explanation of the framework. It is found from Table 7.1 that cybercrime is the most significant influencing factor that causes unanticipated damage to businesses and individuals. Further, security breaches, identity theft, economic theft, and internet time fraud are among the most frequent types of cyber theft. “The term “internet time fraud” is a synonym of the word “Internet time theft”. It defines the type of theft in which an unauthorized person uses the internet and accesses login details without that person's knowledge, either through hacking or illegal means. This might include things like reading personal emails on a regular basis, browsing non-work-related topics, and spending too much time on social media platforms (when it is not an essential part of the work)”. Although cybersecurity is progressing every day, hackers constantly boost their level and discover new ways to break into new systems. This highlights the significance not only of better cybersecurity technology but also of strong cyber jurisprudence. Furthermore, in order to reduce cybercrime and fraudsters' efforts, policymakers must be aware of potential cybersecurity vulnerabilities and rectify them in real-time. Consistent efforts and persistent vigilance are required to control the rising risks across the country.

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As per the India cybersecurity rules and regulations described above, the government has been seeking to establish stronger jurisprudence to enable enterprises to protect data from the current cyber threats (Lezzi et al., 2018; Sharma et al., 2021). It is recommended that companies become more proactive in terms of software and data security. Cyber hackers are always on the lookout, and their methods of assault are growing more complex. For the same purpose, organizations should conduct frequent checks on their systems to detect any flaws and rectify them as soon as possible. Its purpose is to enhance cybersecurity through increasing information-sharing regarding cybersecurity risks and for other objectives. These laws confirmed that all the regulatory agreements, including cyber forensics, e-discovery, and cybersecurity vigilance, are well-covered by the law.

Table 7.1 IT Act guidelines by Indian legislation

Act	Description	References
Section 43	People who attack computer systems without the owner's authorization are liable to this law. In such instances, the owner is entitled to full recompense for the entire loss.	Biasiotti et al. (2008); Contissa et al. (2021)
Section 66	This section applies to a person who is found to have committed any of the acts listed in section 43, such as dishonestly or fraudulently. In such cases, the penalty might be up to three years in prison or a fine of up to Rs. 5 lakh.	Biasiotti et al. (2008)
Section 66B	Consolidates the penalties for receiving stolen digital devices or systems in a fraudulent manner, which affirms a possible three-year imprisonment. Based on	Biasiotti et al. (2008)

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	the severity, this period can also be accompanied by a fine of Rs. 1 lakh.	
Section 66C	This section will look into security breaches involving impostor digital signatures, password hacking, and other unique identification elements. If found guilty, three-year imprisonment could be accompanied by a fine of Rs.1 lakh.	Biasiotti et al. (2008)
Section 66D	This section was developed on-demand to punish criminals who use virtual machines to impersonate other people.	Biasiotti et al. (2008)

7.2.4.2 Implementation of legal informatics through semantic web

The current development has shifted from a text-based web into a semantic web. This implies that legal information that exists on the internet is progressively handled based on its content rather than just as a sequence of words. This is generally accomplished by embedding particular computer-readable specifications in natural language text, which can then be analyzed in a variety of ways (Biasiotti et al., 2.008). These ways are obtaining the document, accessing associated information, identifying the document's legally binding information, and following the rules.

The semantic web aims to make it accessible for everyone to access the web's benefits, including human communication, business processes, and information exchange systems. Furthermore, it is also allowing access to the web from every device (including telephones, and television systems). Moreover, allowing the web to be accessed not just by people but also by computers by integrating machine-processable data. Finally, trust and confidence, or the ability to conduct transactions that are transparent, secure, and private. The legal semantic web is made up of the legal material that is available on the internet. Information or data are available on the web that have been enhanced with machine-processable content. These standards are being developed to identify funds and assets so that each legal document issued by any legal authority may be verified unambiguously. Over the implementation of the legal semantic web, it will likely improve the functionality of certain information by facilitating the automatic retrieval of appropriate legal data. In the coming years, all participants in the legal domain, when seeking legal data, will explore the legal semantic web and be given legal data that has been moulded to some point by Industry 4.0 processes.

7.2.4.3 Implementation of legal informatics through sustainable legal-tech

"Sustainable legal-tech" is defined as an effective judicial process that is strengthened and integrated with the most cutting-edge computing and informatics technologies and methods. The main purpose of sustainable legal-tech is to make the process more efficient, economically viable, and accessible to even the most marginalized members of society. The judicial system, with its elevated privileges to all aspects of society, is particularly situated to advance global sustainability objectives. Lawyers have a responsibility to use their expertise and abilities for the greater good while defending their clients' personal interests (Hongdao et al., 2019). This implies seeking solutions for their clients' social, economic, and environmental issues, as well as contributing some of their efforts to sustainable initiatives. Lawyers need to understand new skills and become more aware of their own and their clients' environmental impact. Also, lawyers must apply their experience for constructive use by finding solutions to environmental and social problems. The law firms must defend human rights, support in the removal of impediments to justice, and resist challenges to the profession's independence. The following measures must be upheld to ensure the legal profession's long-term sustainability:

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- Lawyers must maintain a high standard to fight corruption and outside intervention. Further, lawyers must have the freedom to accept or reject a case, to make decisions on behalf of their clients, and to avoid any conflicts of interest.
- Lawyers must be prepared to face the problems of a globalized and complex environment. They must be dedicated to knowing, appreciating, and assuring respect for diverse cultures and legal systems. By encouraging the exchange of legal skills, lawyers may embrace and ensure a diverse range of viewpoints.
- Lawyers may be the primary defenders of the judicial system and of the just advancement of contemporary legal societies. These are the structure parts of a flourishing economy and society. It is the role and endeavor of the lawyer to give access to justice and to assist citizens in overcoming any impediments.
- The judicial system is dedicated to continuous learning and improvement. Lawyers should enhance their legal knowledge with a thorough understanding of the issues confronting the many organizations they advise, and they should continue to learn throughout their professions.

On the other hand, the traditional judicial process produces a huge amount of carbon footprint in terms of paperwork and electricity utilization. As per the report presented by the legal sustainability alliance (LSA) 2018, the legal firms were produced 1.92 lacs tonnes of CO2 emissions. Legal-tech in all aspects of triple-bottleneck has contributed and can continue to support law firms reduce their environmental impact. It is found that legal-tech implementations and supporting technologies may help law firms drastically reduce their carbon emissions from air travel. Digitalized legal information is independent of its conventional paperwork that can be managed by computer and spread across connected devices. The internet has become one of the most essential sources of legal data for advocates and individuals. Various statutory texts, a large body of case law, and a plethora of opinions on laws and cases may all be found on the

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internet (there is an enormous developing amount of digitalized legal policy). The internet is rapidly becoming a vast collection of legal information and an open platform for debating legal problems. According to research on legal software programs, there are a variety of apps available, ranging from access to law manuscripts and judicial decision methods for analyzing law firms (e.g., case management and time management). However, technological advancements have made it possible for legal firms to make the transition to become more sustainable. Further, the execution of Industry 4.0 technologies may make law firms more sustainable. It is achieved by reducing the use of paperwork, reducing energy consumption, allowing for further outsourcing, and increasing workplace flexibility.

7.3 Issues in Implementing Industry 4.0 and Legal Informatics

The legal and ethical issues greatly affect the entire process of the current judicial system. These issues are prevalent in the form of human rights exploitation, corruption, unfair and biased practices, etc. Additionally, the inadequate number of judges for handling a large number of pending cases causes delays in the judicial process, indirectly providing space for these issues. According to Sharma et al. (2021), legal responsibilities of the judicial system are to provide fair, transparent, efficient and unbiased justice timely as well as reasonable manner. Further, with the involvement of modern technology in the LI, the chances of mismanaged confidential information, case files and data theft through cybercrime are always there. Therefore, the execution of Industry 4.0 technologies in the LI may provide adequate and effective solutions to improve the effectiveness of the present judicial system. These technologies may provide substantial efforts to major legal changes in data protection, IT security, labour law and product liability. In addition, the complexity of our current legal system cannot be solved only by technology development. It can be solved by making a solid legislative justice system that utilizes the capabilities of Industry 4.0. Table 7.2 present the legal and ethical issues while

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implementing Industry 4.0 concepts. It is evident from Table 7.2 that while executing Industry 4.0 technologies in the LI domain, cybersecurity and data governance are the important factors. The primary objective of cybersecurity legislation is to make it mandatory for businesses and organizations to protect their systems and data from cyber-attacks such as malware, hacking, extortion, denial of service attacks, unauthorized access and control system threats. Further, it is important to develop a cybersecurity enhancement act to implement a voluntary public-private partnership. It aims to promote cybersecurity by bolstering cybersecurity research and development, employee education and training, and public awareness campaigns and preparation.

Additionally, product liability may be an important criterion for the LI system that follows the digital revolution of the judicial processes to prudently study all of the legal issues. This may contain risks that stem from the incorporation of external agencies in the LI regarding data protection, security and agreements on liability. Also, labour law protects the rights of the employees, employers and trade unions.

Table 7.2 Legal and ethical issues in the espousal of Industry 4.0 and legal informatics

Factors	**Description**	**References**
Cybersecurity	The cybersecurity technique is affected by various types of threats such as phishing attacks, integrity attacks, adversarial assaults, zero-day exploits and malware attacks.	Schmidt et al. (2015); Tao et al. (2019); Kaplan et al. (2020); Ghobakhloo et al. (2020)
Data protection and transparency	The concept of transparency implies that any information delivered to the citizens or the data subject be concise, easily available, and understandable as well as the use of simple and transparent language.	Tao et al. (2019); Dixit et al. (2021)

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Data governance	Data governance is defined as a technique to "exercise authority and control over data management".	Abraham et al. (2019); Ender et al. (2021)
Data management	Data management refers to the "development, implementation, and monitoring of plans, strategies, programmes, and practices that control, manage, deliver, and increase the value of data and information resources".	Abraham et al. (2019); Ender et al. (2021)
Product liability and standardization	Product liability is the field of jurisprudence which controls the liability of companies that are responsible for putting items into circulation and are accountable for damage caused by defective products.	Contissa et al. (2021); Seipel et al. (2004)
Labour law	Government agencies impose labour laws such as legislation, or judicial which protect the rights of employees, employers and trade unions.	Sahu et al. (2022); Sharma et al. (2021)

7.4 Process and Control Factor

In the application of Industry 4.0 in the legal domain, many procedures and controlling factors are affected. These factor plays an essential role in strengthening the LI. The following factors are mentioned below.

- Interoperability: in this process, all the legal documents, files and important information related to the case are interconnected to the cyber-physical systems and IoT. It facilitates information exchange and develops communication and standardization between machines and humans. It also interprets and translates the machine language into the common language (Gattullo et al., 2019).
- Real-time monitoring: case-related information is collected and examined on a real-time basis. It helps to allow the progress of the case to be monitored and examined in real-time

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in order to respond quickly to errors, changes in the laws and policies, and so on (Tao et al., 2019).

- Virtualization: a virtual copy of the physical environment is generated by connecting CPSs to virtual facilities and computational techniques, allowing CPSs to monitor physical processes and inform users. As a result, a digital copy of the technical documentation is required (Sharma et al., 2021).
- Decentralization: As the growing requirement for specific items develops, it becomes more important to manage systems from a particular region. Therefore, embedded computers allow CPSs that can make decisions on their own. Activities are only delegated to a higher level in the event of failure (Sharma et al., 2021; Gattullo et al., 2019).

7.5 Results and Discussion

Current study found that how Industry 4.0 technologies became the primary innovator in the legal profession by providing a variety of revolutionary legal solutions. As a result, the ability to develop a new legal justice system and jurisprudence model increases. Accepting digital signatures as legal authentication is a big step in the right direction. This has far broader objectives, including other technologically driven authentication methods like biometrics. Furthermore, the widespread use of electronic fund transfers and data storage proved the need for and accomplishment of the IT Act's futuristic vision. A strong assessment allows for the possibility that IT law will profoundly alter society's information infrastructure, with significant implications for the legal system. Moreover, sustainable LI aims to make the process more efficient, economically viable, and accessible to even the most marginalized members of society.

A significant role of LI is to study the collaboration of law and technology and develop an understanding that has both practical and theoretical aspects (Seipel et al., 2004). Furthermore,

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LI provides an opportunity for the growth of IT law in the future. In a nutshell, LI enables conventional approaches to dealing with IT-related legal systems to be supplemented and enhanced. Moreover, allowing LI to incorporate both regulatory elements of IT use and its applications in the field of law will enhance the field's advancement.

Three research questions were asked in this research – To answer the first research question (RQ1). AI can significantly reduce the time and expense of legal activity. In the future, more specialized service agreements application cases and increasingly sophisticated AI will unlock value with higher-order findings that lead to better-negotiated results, and higher profit collection in the future research. The cloud computing network delivers streamlined and tailored services to the lawyers which can provide unprecedented transparency, real-time monitoring and storage capacity of the existing cases. Moreover, Big Data technology may be helpful in decision-making based on data interpretation, data governance and prediction for the legal organizations. Legal professionals can also utilize a vast database of legal firms' billing details for benchmarking, case evaluation, and improvement in efficiency. Further, Big data technologies have a lot of potential to expedite the traditional legal justice system and address information gaps while fastening courtroom procedures and improving real-life legal duties (Sharma et al., 2021). The primary objective of cybersecurity legislation is to make it mandatory for businesses and organizations to protect their systems and data from cyber-attacks such as malware, hacking, extortion, denial of service attacks, unauthorized access and control system threats. Moreover, it is important to develop a cybersecurity enhancement act to implement a voluntary public-private partnership that aims to promote cybersecurity by bolstering cybersecurity research and development, employee education and training, and public awareness campaigns and preparation. For the second research question (RQ2), there are significant gaps in the identification of legal issues in the current legal judicial system. Product liability, data protection and IT security, labour jurisprudence and intellectual property are the

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major legal issues that may be affected by implementing Industry 4.0 and LI concepts. For the third research question (RQ3), the proposed framework will guide the judicial system and lawmakers to espouse Industry 4.0 technologies for improving the existing legislative system. Using emerging technologies, lawyers can track the real-time status of running cases and provide decision-making support. Further, a lawmaker can develop new strategies using cloud-based data sources and develop agendas for upcoming cases.

The legal framework will need an extensive approach to technological developments in computer systems or risk a scattered, disorganized approach. Particular challenges will arise in licensing, liability, security, accessibility, and managerial and administrative control. Despite these challenges, the benefits of information systems in terms of data safety and risk mitigation make it critical that the legal framework find ways to encourage the use of computerized information systems without jeopardizing data safety. Additionally, it is necessary to implement e-Law projects to reform legal text creation by establishing a continuous electronic production frequency with a uniform structure developed on the same electronic text foundation from draught to Internet promulgation (publication). A strong legislative document standard specifies a set of simple, technology-neutral interpretations of judicial records for e-Parliament services. It is facilitating a structure for the effective exchange of “machine-readable” judicial records like jurisprudence, debate records, and minutes, etc. Enabling access to important legal papers or documents is not only the issue of providing physical or online access. As already mentioned, “open access” mandates the description and classification of information in a consistent and orderly manner, such that content is grouped into meaningful pieces that can be interpreted by application software, and the data is made “machine-readable. In addition, a lack of study has been found on the integration of Industry 4.0 and sustainable legal-tech. The implementation of Industry 4.0 technologies will make law firms more sustainable.

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7.6 Concluding Remarks

The research work found that the present legal justice system does not address the legal and ethical issues of implementing legal informatics. Further, cybersecurity and data governance are the major issues while implementing these concepts. The government must be seeking to establish stronger jurisprudence to enable enterprises to protect data from the current cyber threats. It is recommended that companies become more proactive in terms of software and data security. In addition, the implementation of Industry technologies, including AI and cloud computing provides a structure for legal informatics systems that fulfill the requirements of clients and lawmakers. Furthermore, legal technologies (Legal tech Industry 4.0 technologies) reduced the communication gap between legal firms and clients. They provided sustainable as well as virtual collaborative solutions by allowing lawyers, such as prosecutors, counsellors, and advisors, to obtain information relevant to cases on which they are working together (Hongdao et al., 2019).

7.6.1 Future research directions

The judicial system is one of the few sectors that has been hesitant to adapt to the new standard. Since COVID-19 affects every industry, it may be time for legal professionals to usher in change and migrate to cloud-based solutions. The combination of law and technology implies a need for lawyers to enhance their skill sets. In order to survive in a diverse workplace, in-house legal professionals may need to broaden their knowledge beyond law articles and desktop research, as evidenced by the entry of data scientists, software engineers, and computer programmers. Further, Lawyers must now connect with modern technology and other specialists from various sectors. Cloud computing and AI have the ability to transform the legal sector, and the only way to survive in a post-pandemic digital environment is to constantly upgrade oneself.

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Additionally, lawyers, IT professionals, academia, and students need to renew their efforts to take information technology in innovative and constructive directions. The law follows a similar path as technology develops. The legal system finds the most analogous preceding technology and then evaluates if the new technology fits into that classification. The problem arises because the law employs its own classifications of technologies, the majority of which emerged at a specific period in the technological development cycle. The most complicated technico-legal problem arises when a new technology is embedded in a regulatory framework. The future research direction is specified as follows:

- In order to provide proactive legal care, a lawyer must interact closely with people from various backgrounds, professions, and disciplines.
- In order to be effective implementation of LI, the lawyer's advice, questionnaires and responses must all be delivered in a way that everyone understands.
- Future studies should be performed to investigate the feasibility of LI in developing countries.
- The combination of electronic documents in the judicial process improves the management ability of the legislative workflow.
- The push toward the semantic web, i.e., the improvement of records with machine-processable data, can make legislative records more accessible and used unprecedentedly.

7.6.2 Limitations of the study

The present study has a couple of limitations. Firstly, the present study has considered only a theoretical perspective for developing the framework. In future studies, a quantitative decision-making model can be utilized to validate the findings. Secondly, the identified issues may be explored further in future research to evaluate their causal and dependent relationships. The sensitivity analysis may also be conducted for sustainable LI modelling.

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7.6.3 Research implications

The findings of the research propose important legal implications. Previous research has concentrated on the emergence of legal technology and the associated opportunities for the legal industry. Although, it is found that very few studies have considered the specific implications for clients and lawyers. Legal tech has challenged monopolies in the legal sector, resulting in a competitive environment that requires continuous product development and cost reduction. Finally, it should be highlighted that the use of contemporary IT in jurisprudence helps to create more advantageous conditions for lawyers working in this field as well as legal institutions who seek legal advice. Client confidence in jurisprudence, legal tech services, and business models created during the fourth industrial revolution can be strengthened by the law.

Chapter 8

Development of Performance Framework for Measuring the Circularity of Industry 4.0 and Circular Economy

8.1 Introduction

The chapter deals with the development of Industry 4.0 and CE performance measurement systems based on triple bottom line (TBL) perspectives of the sustainable development. Sustainability has become a significant aspect for manufacturing organizations with growing awareness of environmental rules and regulations and the globalization of markets. Whereas considering sustainable development aspects, organizations are more concentrated towards the linear supply chain operations and give less attention towards the circular supply chain. The Global Reporting Initiative's rules endorse this concept since both its core indicators and their additional indicators are broad and focused on forward flows. Conversely, CE and Industry 4.0 have the potential to considerably improve an organization's long-term sustainability. It is found from the literature review that most of the studies consider only the economic or environmental performance measure factors for the adoption of industry 4.0 and circular economy. Centobelli et al. (2020) stated, "There is a gap in quantitatively modelling social impacts together with environmental and economic impacts". Luthra and Mangla (2018) also observe that there is a limited study focusing on social perspectives of sustainable development. The research attempted to fill these gaps by developing a model for estimating the performance measure of Industry 4.0 and CE from the viewpoint of TBL aspects of sustainable development.

8.2 Graph Theory and Matrix Approach

Several authors have utilized the various MCDM approaches, namely AHP, ANP, ELECTRE,

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DEMATEL, TOPSIS and PROMETHEE. Rao (2007) developed the graph theory and matrix approach (GTMA) methodology for the selection of material and estimating material suitability index. Kumar et al. (2022) explored the major barriers to the application of big data analytics using GTMA. It is a laborious and coherent decision-making approach, i.e. useful in examining directional graphs. In addition, its accuracy improves with a greater number of nodes. In various fields of industrial engineering and management, graph or digraph model representations have been shown to be beneficial for modelling and investigating various types of attributes and issues (Rao, 2007). When a graph or digraph is complicated, graphic investigation develops stimulating. The matrix technique may be used on a computer to do this. Nodes and edges are two important elements of GTMA that represent the inter-relationship among various nodes by using a digraph and a matrix. The attributes are denoted by these nodes. A digraph representing these attributes and their relations is established with the selection of attributes. The number of nodes (M) in the digraph corresponds to the number of attributes that are evaluated by using an arrow or directed edge connecting the two nodes that show their relative significance.

The implementation of industry 4.0 in the CE is the nascent stage of development. The main purpose of industry 4.0 implementation is to improve the circularity of products by using real-time monitoring and data exchange, which improves real-time monitoring and risk mitigation throughout the supply chain. Smart manufacturing employs technologies based on the cyber-physical-systems and internet of things to organize workstation sequences, optimize assembly lines, regulate production processes, and schedule deliveries and vehicle movements. On the other hand, Kirchherr et al. (2017) defined CE in terms of social, economic and environmental perspectives. In addition, the 4R framework of CE was proposed, which encompasses the processes taken to achieve circularity, such as reduction, reuse, and recycling. Bag et al. (2021) also identified 10R of the CE in the application of industry 4.0. Agrawal et al. (2016) observed disposition decisions in reverse logistics and prioritized the five alternatives through GTMA.

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Chhimwal et al. (2021) measured the circularity decisions using the Bayesian Network and analyzed the risk management in circular supply chain in the automobile industry. Sahu et al. (2022) combined industry 4.0 and CE and proposed the transition framework. In this study, the author identified and analyzed several implementation challenges and enablers. Singh et al. (2021) identified the strategic issues while implementing Big Data in the healthcare industry. The circularity alternative is selected, which accounts for the number of attributes. In accordance with the literature review and experts' opinions,Table 8.1 shows the five alternatives of circularity which are selected for the research.

Table 8.1 Alternatives of the circularity

Alternatives	**Description**	**Reference**
Refurbished	The word "refurbish" refers to the method of updating an older product.	Govindan et al. (2016); Bag et al. (2021)
Recycling	Recycling is a technique of handling resources in order to produce a product of the same or lower quality.	Agrawal et al. (2016); Kirchherr et al. (2017)
Reducing	Reduce means the lesser amount of natural assets used in production.	Govindan et al. (2016); Kirchherr et al. (2017)
Repairing	Repair refers to the process of fixing and maintaining a faulty product so that it can be utilized in its original capacity.	Bag et al. (2021); Sahu et al. (2022); Chhimwal et al. (2021)
Recovering	Recovering uses the incineration of material for energy recovery.	Agrawal et al. (2016); Govindan et al. (2016)

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In addition, the circularity attributes that impact the above-mentioned alternatives are shown in Table 8.2. It is found from Table 8.2 that digitalization, data security and privacy, management support and sustainable development are the major attributes while implementing circularity in theorganization. The majority of the prior attributes for selecting circularity alternatives are based onorganizational requirements.

Table 8.2 Attributes for the selection of optimum circularity alternative.

Attributes	**Description**	**Reference**
Digitalization	It is a main facilitator of Industry 4.0, and it provides real-time information on the product and its usage pattern. In addition, information about the product's quality, volume, and remaining life of the product.	de Sousa Jabbour et al. (2018); Nascimento et al.(2019); Kumar et al. (2022)
Complexity in collaboration	It shows an important character in the incorporation of industry 4.0 and CE.	de Sousa Jabbour et al. (2018); Sahu et al. (2023b)
Data security and privacy	It provides safety and privacy for all interfacing networks and safe organizations from unwanted thefts.	Agrawal et al. (2022)
Data management	It transforms the unstructured data into structured form.	Sivarajah et al. (2022); Singh et al. (2021)
Supply chain strategies	It develops the strategies for the success of circular products using industry 4.0 for making environmentally sustainable	Govindan et al. (2016); Nascimento et al. (2019)

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	manufacturing.	
Customer behaviour	Customer behaviour or attitude is more important in the circular supply chain than in the forward supply chainbecause of the quality of used or returned products.	Agrawal et al. (2016); Chhimwal et al. (2021)
Management support	It is crucial to pay attention to what competitors do with returned items and how they treat them. Selling recycled items on the market can be a green approach, but it can also have an impact on a product's brand image, depending on market conditions.	Agrawal et al. (2016); Sahu et al. (2022)
Social	It offers social responsibility, workload distribution, health standards and working environment conditions.	de Sousa Jabbour et al.(2018); Bag et al. (2021); Chhimwal et al. (2021)
Economic	It provides profit sharing, revenue generation and forecasting price strategies of the products.	Sahu et al. (2022); Agrawal et al. (2016)
Environmental	It impacts on ecological performance and reduces the adverse effect on the environment by resource extraction.	Kirchherr et al. (2017); Nascimento et al. (2019)

8.3 Case Illustration

A barrel manufacturing organization XYZ has been selected to illustrate the proposed

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methodology. The present organization is selected because of the largest manufacturer of steel barrels in developing countries like India. XYZ is a market leader in steel barrels manufacturing with a total 45% market camp. The organization has an annual turnover is more than 500 Million INR. The organization has a primary objective to become a leading industry in Asia and is placed among the top ten organizations in the global market for manufacturing steel barrels. Further, the organization has always emphasized R&D in order to develop environmentally friendly and biodegradable products and implement zero waste in their production environment. According to figures released by the human resource department, the current demand for barrel products will expand by up to 35 percent over the next two decades. The manufacturing unit of this organization was established in the early period of the twentieth century, and approximately 10,000 employees are working in this organization.

In order to employ the proposed methodology, suitable circularity alternatives related to steel barrel for XYZ organization is identified and analyzed. These alternatives are refurbished; recycled; reduced; repaired; and recovered. Five experts from the manufacturing organization were selected to provide the values of diagonal and off-diagonal elements. These experts have wide experience of approximately 10 years in the production, manufacturing and marketing field.

8.4 Results and Discussion

The digraph is comprised of a set of nodes N =
$\{n_i\}$, where i = 1,2,3,. M and a set of directed edges E = $\{a_{ij}\}$.

Step 1: Identify and analyze the attributes and alternatives which are concerned with the decision-making problem.

The following circularity alternatives are: Circularity alternative 1 (A-1): Refurbished; Circularity alternative 2 (A-2): Recycle; Circularity alternative 3 (A-3): Reduce; Circularity alternative 4 (A-

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4): Repair; Circularity alternative 5 (A-5): Recover.

Similarly, circularity attributes are: Circularity attributes 1 (C1): Digitalization; Circularity attributes 2 (C2): Complexity in collaboration; Circularity attributes 3 (C3): Data security and privacy; Circularity attributes 4 (C4): Data management; Circularity attributes 5 (C5): Supply chain strategies; Circularity attributes 6 (C6): Customer behaviour; Circularity attributes 7 (C7): Management supportCircularity attributes 8 (C8): Social; Circularity attributes 9 (C9): Economic Circularity attributes 10 (C10): Environmental.

Step 2: Develop the attributes diagraph.

In order to develop the attributes diagraph, Figure 8.1 represents the digraph of inter-relationship among the different circularity attributes.

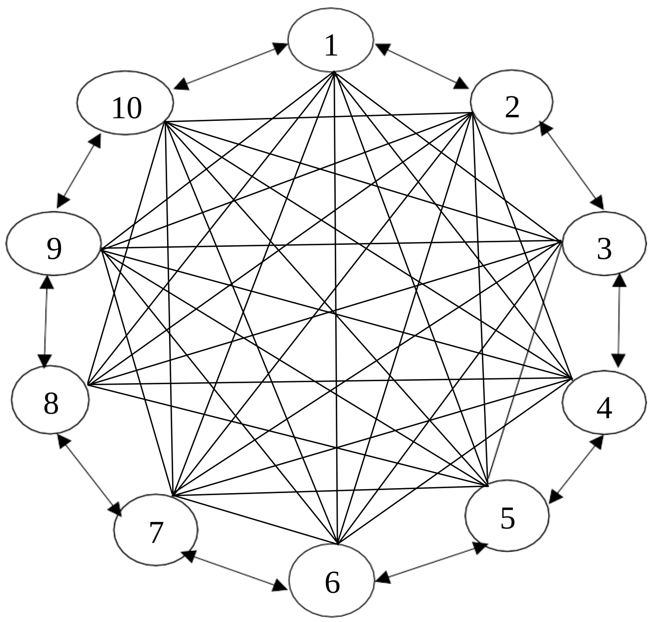

Figure 8.1 Inter-relationship digraph for circularity attributes

Step 3: Find the permanent function for the attributes matrix.

Evaluate the relative importance of circularity attributes on an appropriate scale. The scale for the relative importance is represented in the six types, which are shown in Table 8.3. Table 8.3 will be used to consider the values of the matrix [A] of off-diagonal entries. Similarly, Table 8.3 shows

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therelative importance of circularity alternatives.

Where, S_{ij} = relative importance value and a_{ij} = relative importance value

Table 8.3 The scale of the relative importance of various attributes

Class description	Relative importance	
	aij	1-aij
Two attributes are equally important	0.5	0.5
One attribute is slightly more important than the other	0.6	0.4
One attribute is strongly more important than the other	0.7	0.3
One attribute is very strongly important than the other	0.8	0.2
One attribute is extremely important than the other	0.9	0.1
One attribute is exceptionally more important than the other	1	0

Table 8.4: Value of attributes for each circularity alternative

Subjective measure of attribute	Assigned Value of Sij
Exceptionally less importance	0.0
Extremely low importance	0.1
Weakly importance	0.2
Fairly importance	0.3
Moderate importance	0.4
Average importance	0.5
Above average importance	0.6
High importance	0.7
Very high importance	0.8

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Strongly high importance	0.9
Absolutely high importance	1.0

$$[A] = \begin{array}{c} \\ C1 \\ C2 \\ C3 \\ C4 \\ C5 \\ C6 \\ C7 \\ C8 \\ C9 \\ C10 \end{array} \begin{array}{c} \begin{array}{cccccccccc} C1 & C2 & C3 & C4 & C5 & C6 & C7 & C8 & C9 & C10 \end{array} \\ \begin{bmatrix} S1 & 0.5 & 0.7 & 0.8 & 0.5 & 0.8 & 0.7 & 0.5 & 0.9 & 0.7 \\ 0.5 & S2 & 0.5 & 0.6 & 0.8 & 0.6 & 0.6 & 0.8 & 0.6 & 0.5 \\ 0.3 & 0.5 & S3 & 0.9 & 0.5 & 0.5 & 0.4 & 0.5 & 0.8 & 0.5 \\ 0.2 & 0.4 & 0.1 & S4 & 0.6 & 0.7 & 0.9 & 0.6 & 0.8 & 0.6 \\ 0.5 & 0.2 & 0.5 & 0.4 & S5 & 0.6 & 0.8 & 0.9 & 0.7 & 0.5 \\ 0.2 & 0.4 & 0.5 & 0.3 & 0.4 & S6 & 0.6 & 0.8 & 0.6 & 0.5 \\ 0.3 & 0.4 & 0.6 & 0.1 & 0.2 & 0.4 & S7 & 0.9 & 0.7 & 0.5 \\ 0.5 & 0.2 & 0.5 & 0.4 & 0.1 & 0.2 & 0.1 & S8 & 0.7 & 0.5 \\ 0.1 & 0.4 & 0.2 & 0.2 & 0.3 & 0.4 & 0.3 & 0.3 & S9 & 0.8 \\ 0.3 & 0.5 & 0.5 & 0.4 & 0.5 & 0.5 & 0.5 & 0.5 & 0.2 & S10 \end{bmatrix} \end{array}$$

Step 4: Substitute the value of S_i and find the value of permanent functions.

The value of a permanent function of an M X M, i.e. [A] with attributes a_{ij} is represented by:

$$\text{Per (A)} = \sum_P \prod_{i=1}^{N} a_i \; P(i)$$

A C++ programme will be used to evaluate the value of permanent functions for each alternative.

Table 8.5. Diagonal elements values for each disposition alternative

Attributes	A-1	A-2	A-3	A-4	A-5
Digitalization	0.9	1	0.8	0.9	1
Complexity in collaboration	0.6	0.5	0.4	0.7	0.6
Data security and privacy	0.9	1	0.8	0.7	0.9
Data management	0.8	0.7	0.5	0.8	0.9
Supply chain strategies	0.4	0.6	0.3	0.6	0.5
Customer behavior	0.8	0.6	0.8	0.5	0.7
Management support	0.7	0.9	0.6	0.8	0.6
Social	0.6	0.5	0.8	0.4	0.8

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Economic	0.9	0.7	0.9	0.8	1
Environmental	0.4	0.5	0.4	0.6	0.5

A-1 =

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.9	0.5	0.7	0.8	0.5	0.8	0.7	0.5	0.9	0.7
C2	0.5	0.6	0.5	0.6	0.8	0.6	0.6	0.8	0.6	0.5
C3	0.3	0.5	0.9	0.9	0.5	0.5	0.4	0.5	0.8	0.5
C4	0.2	0.4	0.1	0.8	0.6	0.7	0.9	0.6	0.8	0.6
C5	0.5	0.2	0.5	0.4	0.4	0.6	0.8	0.9	0.7	0.5
C6	0.2	0.4	0.5	0.3	0.4	0.8	0.6	0.8	0.6	0.5
C7	0.3	0.4	0.6	0.1	0.2	0.4	0.7	0.9	0.7	0.5
C8	0.5	0.2	0.5	0.4	0.1	0.2	0.1	0.6	0.7	0.5
C9	0.1	0.4	0.2	0.2	0.3	0.4	0.3	0.3	0.9	0.8
C10	0.3	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.2	0.4

A-2 =

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	0.5	0.7	0.8	0.5	0.8	0.7	0.5	0.9	0.7
C2	0.5	0.5	0.5	0.6	0.8	0.6	0.6	0.8	0.6	0.5
C3	0.3	0.5	1	0.9	0.5	0.5	0.4	0.5	0.8	0.5
C4	0.2	0.4	0.1	0.7	0.6	0.7	0.9	0.6	0.8	0.6
C5	0.5	0.2	0.5	0.4	0.6	0.6	0.8	0.9	0.7	0.5
C6	0.2	0.4	0.5	0.3	0.4	0.6	0.6	0.8	0.6	0.5
C7	0.3	0.4	0.6	0.1	0.2	0.4	0.9	0.9	0.7	0.5
C8	0.5	0.2	0.5	0.4	0.1	0.2	0.1	0.5	0.7	0.5
C9	0.1	0.4	0.2	0.2	0.3	0.4	0.3	0.3	0.7	0.8
C10	0.3	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.2	0.5

A-3 =

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.8	0.6	0.7	0.8	0.4	0.9	0.7	0.6	1	0.8
C2	0.5	0.4	0.5	0.7	0.9	0.6	0.6	0.7	0.6	0.6
C3	0.3	0.5	0.8	1	0.6	0.4	0.6	0.4	0.9	0.5
C4	0.4	0.3	0.2	0.5	0.5	0.6	1	0.4	0.7	0.5
C5	0.6	0.1	0.4	0.2	0.3	0.5	0.9	0.8	0.6	0.4
C6	0.3	0.5	0.5	0.4	0.6	0.8	0.7	0.9	0.4	0.6
C7	0.4	0.4	0.2	0.6	0.3	0.5	0.6	0.9	0.7	0.6
C8	0.6	0.4	0.2	0.4	0.2	0.1	0.4	0.8	0.5	0.8
C9	0.2	0.5	0.6	0.4	0.1	0.3	0.6	0.6	0.9	0.6
C10	0.4	0.6	0.4	0.5	0.7	0.8	0.5	0.6	0.3	0.4

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A-4 =

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1										
C2	0.6	0.7	0.4	0.8	0.6	0.7	0.4	0.8	0.4	0.3
C3	0.4	0.8	0.7	1	0.4	0.6	0.5	0.7	0.9	0.6
C4	0.3	0.5	0.2	0.8	0.8	0.5	0.7	0.6	0.7	0.4
C5	0.7	0.4	0.3	0.4	0.6	0.6	0.7	0.9	0.5	0.5
C6	0.4	0.2	0.6	0.4	0.4	0.5	0.8	0.6	0.7	0.6
C7	0.4	0.3	0.5	0.2	0.4	0.3	0.8	1	0.6	0.4
C8	0.6	0.4	0.2	0.6	0.2	0.4	0.2	0.4	0.4	0.3
C9	0.2	0.5	0.4	0.1	0.5	0.6	0.2	0.1	0.8	0.6
C10	0.5	0.3	0.2	0.6	0.4	0.2	0.3	0.6	0.4	0.6

A-5 =

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	0.6	0.4	0.5	0.6	0.9	0.4	0.3	0.8	0.6
C2	0.3	0.6	0.4	0.6	0.4	0.2	0.8	0.6	0.5	0.3
C3	0.2	0.6	0.9	1	0.4	0.2	0.6	0.3	0.6	0.2
C4	0.4	0.6	0.2	0.9	0.4	0.5	0.7	0.2	0.4	0.8
C5	0.3	0.8	0.7	0.2	0.5	0.9	0.6	0.7	0.9	0.4
C6	0.5	0.3	0.6	0.7	0.2	0.7	0.5	0.6	0.7	0.6
C7	0.4	0.4	0.3	0.2	0.6	0.5	0.6	0.8	0.9	0.4
C8	0.3	0.1	0.7	0.6	0.4	0.3	0.2	0.8	0.5	0.6
C9	0.5	0.6	0.4	0.1	0.5	0.7	0.8	0.2	1	0.6
C10	0.5	0.3	0.8	0.2	0.8	0.8	0.4	0.7	0.1	0.5

Circularity alternative A-1 = 3907.37

Circularity alternative A-2 = 4478.84

Circularity alternative A-3 = 7039.71

Circularity alternative A-4 = 4521.02

Circularity alternative A-5 = 5679.79

8.5 Concluding Remarks

In the proposed research, the GTMA is used to determine the optimal circularity based on a number of various circularity attributes. The attributes are selected by virtue of an extensive literature review and opinions of industry experts. Equivalent attributes and alternatives are evaluated from the perspective of sustainable development and the application of technologies

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within the context of Industry 4.0 and CE. The effective employment of industry 4.0 technologies in circularity may deliver cost-effective resolutions, reduction of breakdowns, improve supply chain flow and maximize the circularity of resources in the measured barrel manufacturing organization. The implementation of GTMA provides for the managing of a large number of nodes and the interaction of multiple attributes.

Circularity alternative-3, i.e. “reduce” (Circularity index value = 7039.71), has got the highest decision value among all evaluated alternatives for the barrel manufacturing of XYZ organization. Therefore, an organization is implementing the industry 4.0 technologies and working on “reduce” the unusual wastage present in the system. The second circularity alternative is to “recover” with a circularity index value of 5679.79 followed by “repair” (Circularity index value = 4521.02), “recycle” (Circularity index value = 4478.84) and “refurbished” (Circularity index value =3907.37). Govindan et al. (2016) suggested that remanufacturing industries in the developing country, such as India is encouraged by the opportunity for profit. According to Agrawal et al. (2016), remanufacturing products and technologies in India are still in its early stages, and organizationshave yet to accept it as a professional commercial activity.

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Chapter 9

Conclusions and future research directions

9.1 Introduction

In recent years, Industry 4.0 and CE have received a lot of attention because it replaces the end-of-life conception and works towards cleaner production and sustainable development. The successful integration of Industry 4.0 technologies from CE perspective will provide a cost-effective product with reduced power consumption, CO_2 emission and minimum wastage of raw material. It also provides advanced process control, end-to-end visibility, identifies failure and errors, and streamlines production planning which helps organizations in flexibility and agile manufacturing operations. The application of Industry 4.0 and CE are in the primary phase of development, and industries are facing a couple of challenges while implementing these technologies in their industries. Previous research considered the implementation of Industry 4.0 and CE from the Indian viewpoint is very limited throughout the industries. The study pointed to investigating the Indian manufacturing industry and addressing the challenges and issues concerned with implementing Industry 4.0 and CE. Further, it focused on various attributes and sub-attributes to investigate them in-depth with the help of several research techniques, including survey method, case study, and establishment of models and conceptual frameworks.

An extensive literature review and investigation of Indian manufacturing organizations were conducted to encounter various issues and challenges coupled with Industry 4.0 and CE. The literature suggested that some issues had not been given the appropriate amount of attention by academics and researchers. The present study identified and explored these select issues as adoption and implementation, circularity decisions, performance measure and transition as well as legal informatics framework of Industry 4.0 and CE.

According to Rajput and Singh (2019), a number of issues affect the incorporation of CE into Industry 4.0. The occurrence or insufficiency of these factors can be converted into barriers or drivers of Industry 4.0 and CE application in the industry. It is found from the literature that very limited studies are available on key challenging factors for the Indian manufacturing industry. Challenges in the form of technology, operation, organization, managerial and sustainable development in the implementation of Industry 4.0 and CE. CE execution using Industry 4.0 technologies is one of the most effective ways of dealing with these uncertainties. Existing research studies show that several models or frameworks have been established for circularity of resources for reduce, reuse and recycling by incorporating various corporate strategies. Although, very few of them consider the factors such as circularity decisions, percentage circularity and maximum circularity, which can make a very various strategies and may affect circular economy substantially. Through CE implementation, industries may have an awareness of projected business from Industry 4.0 and CE activities in future. The number of used products, service quality and usage pattern of returned products may help in circularity decisions. It is found that Industry 4.0 and CE are not the part of central activities of several industries, and it is a vulnerable phenomenon for circularity. Most of the research is focused on the circularity measure of Industry 4.0 and CE practices, especially collection and disposal. Further, no extensive model is found for decision-making related to adopting circularity fully or partly the Industry 4.0 and CE activities. The additional major aspect is the circularity of waste products or used products that considerably impacts the performance of Industry 4.0 and CE. However, there is limited research performed on the circularity of returned or recycled products. Based on the literature review, it is found that there are limited number of research, which are available on measuring the performance of Industry 4.0 and CE. In light of these challenges, the present study seeks to utilize the survey and case study methods to fill up these gaps. To support the scientific study of the challenges, the research has employed well-developed approaches, including ANP Fuzzy-TOPSIS and GTMA for developing models, and transition as well as legal informatics frameworks. This chapter comprises a synthesis of work carried out and significant research findings. In addition, major contributions, research implications, recommendations of the study along with limitations and future scope of research work are also described.

9.2 Overall Summary

The present research work has developed a transition and integration framework for Industry 4.0 and CE and identified the various factors, which affect the triple bottom line performance of an Indian manufacturing organization. The research has further considered qualitative and quantitative approaches to identify and explore select issues of Industry 4.0 and CE, including the survey method, case study, ANP Fuzzy-TOPSIS and GTMA models. The research work has also developed transition as well as legal informatics frameworks of Industry 4.0. An extensive literature review was performed to investigate the many Industry 4.0 and CE activities and issues related to Industry 4.0 and CE. The methodology to conduct literature review is also discussed in detail.

The literature review methodology along with the categorization of literature on the basis of select issues and challenges, reliability and validity is covered in detail. The research gaps in state-of-art research were identified through an extensive literature review and research objectives were formulated.

- Through an extensive literature review, the transition and integration framework of Industry 4.0 and CE were developed and identified adoption and implementation factors, such as drivers, barriers, enablers, key issues and current challenges.
- The study further utilized and validated the application of survey and case study methods for investigating a wide range of factors, including key issues and performance measures in the Indian manufacturing industry, with the objective of establishing reliability

and validity. A detailed questionnaire was established and responses were collected to ensure the research's reliability, validity, and other significant process parameters for the study. Pilot testing was also conducted to evaluate the feasibility and reliability of the questionnaire. The results from the pilot testing were used to identify and prioritize key challenging factors using an ANP fuzzy-TOPSIS approach.

- Descriptive analysis and hypotheses testing was performed for each construct to check the internal consistency of key aspects of Industry 4.0 and CE implementation in the Indian manufacturing industry along with drivers, barriers, enablers, and selected issues to achieve triple bottom line aspects of sustainability.

- Hypotheses were established in order to examine the fundamental relations and implications of different constructs related to important factors for the Indian manufacturing industry. Further, hypotheses were established for adoption and implementation factors, circularity decisions, and value engineering in order to predict the influence of these variables on the economic, social, and environmental performance of Industry 4.0 and CE. The measurement models for each construct were analyzed to determine the statistical fitness of the data for SEM. The PLSPM technique of SEM was utilized by Smart PLS 3.0 software to test the hypotheses.

- A value engineering approach to measuring the triple bottom line performance of manufacturing industry was utilized. The research aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. The considered methodology is utilized in the case illustration of ABC barrel manufacturing organization with a circular economy perspective. The study reveals that product development costs were reduced by up to 23.91%, and productivity of barrels per day increased by around 150%. Also, power consumption is reduced by 100 KVA, CO_2 emissions by 1825.91 tons/year, water consumption by 96% and total electricity requirement is reduced to 25%. These results may improve the triple bottom line performance of the organization.

- The main objective of the present research is to identify implementation challenges of Industry 4.0 and circular supply chain during the pandemic to achieve sustainable development goals. Based on the comprehensive literature review, combined challenges of implementing Industry 4.0 for developing a CE were identified. A combination of ANP and Fuzzy TOPSIS approach has been selected for the proposed research because a network model with dependence and feedback improves the rankings derived from decisions. The ANP approach has been utilized to evaluate the weights of the criteria using Super Decisions software 2.10 version for reliability and accuracy of the results, while the Fuzzy TOPSIS approach has been used to prioritize the alternatives.

- A model for the selection of optimum circularity alternatives on the basis of various circularity attributes has been established by using GTMA method. On the basis of literature survey and the opinions of the organization's experts, attributes were considered. This method considers the estimation of a permanent function called as circularity index for matrices representing a number of rationally selected circularity alternatives into consideration. The circularity index for various circularity alternatives was evaluated and optimum circularity alternative was considered based on the value of circularity index.

- A framework for legal informatics was developed and analyzed how legal tech Industry 4.0 technologies become an important part of legal informatics systems by providing real-time monitoring and streamlined and tailored services. In the current scenario of increasing digitalization, e-government, and e-commerce, managing LI for long-term performance has become a challenge. A contemporary development in e-government that has substantial implications for the legislative process is the document sharing and application interoperability between the court’s internal users (judges, clerks, etc.) and all its external users (lawyers, eyewitness, etc.). The study investigates the impact of Industry 4.0 emerging technologies that can provide decision-making support for lawyers. The present study proposed a conceptual legal informatics framework to advance and progress the conventional legal justice system. Additionally, the implementation of sustainable legal-tech in the legal domain makes the process more efficient, economically viable, and accessible to even the most marginalized members of society.

9.3 Key Findings from the Research Work

In light of the aforementioned summaries of the study, the major research findings are summarized as follows.

9.3.1 Indian Manufacturing Industry: Survey

It is found from the survey that very limited Indian manufacturing industries focused on Industry 4.0 and CE, which provides a lot of benefits for future research in this area. The study is differentiated across the various industries, however no single industry has been analyzed in detail. Therefore, the present study focuses primarily on the manufacturing industry in India. The findings show that most of the manufacturing organization is implemented Industry 4.0 and CE approaches in their production, while some of them are still dependent on importing the technologies due to many issues and challenges. Some of the major challenges, while implementing Industry are: lack of IT infrastructure, high initial and disposal costs, lack of collaboration and data sharing procedure, and lack of an effective reverse logistic system for implementing Industry 4.0 technologies for achieving CE practices in the organization. The findings of the survey show that Industry 4.0 and CE have become embedded in the strategic planning of many organizations. Several industries are employing CE and Industry 4.0 techniques with the intention of providing better customer satisfaction, improving supply chain processes, identifying failure and error, increasing resource utilization, maximizing the circularity of resources and supporting the longer life of the products. Conversely, there are various factors such as high infrastructure cost, cybersecurity, data transparency, insufficient performance measurement systems, integration with circular supply chain and, other risk or issues associated with the application of Industry 4.0 and CE.

The above-mentioned issues may become the major factors in Implementing Industry 4.0 and CE by certain manufacturing industries.

The research work further explored major challenges in implementation of Industry 4.0 and CE. The most challenging factors were found to be employment disruption, lack of IT infrastructure, high initial disposal cost, insufficient network facilities and big data and analytics. Technological development, organization infrastructure, operational flexibility, managerial awareness and sustainable development are the major key challenging factors for organizations. The survey also revealed that dedicated infrastructure and recycling/redesigning are the two most important Industry 4.0 and CE activities implemented by the organizations.

The results of the hypotheses testing were shown that select issues such as drivers, barriers, enablers, key challenges, and circularity decisions greatly influence the performance of Industry 4.0 and CE. Explanatory factors were found to affect the precision of implementation. Reliability and accuracy in implementing Industry 4.0 and CE are positively related to the economic, social and environmental performance of the organizations. The effectiveness of circularity decisions was influenced by the adoption and implementation factors, and it was positively related to the triple bottom line performance of the Industry 4.0 and CE, respectively. Hypotheses were tested for the integration with circularity decisions and their potential impact on triple bottom line performance. It was also observed that circularity could improve the effectiveness of Industry 4.0 and CE.

9.3.2 Barrel manufacturing organization: Case study

The case study proposed a value engineering methodology that integrates CE concepts to fulfill sustainable product development objectives. The study finds that CE approaches are helpful in product development by maximizing the circularity of resources and reducing the requirement for virgin materials for the successive process of product development. In this perspective, new product development allows material resources to circulate across a manufacturing system.

The study aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. The study revealed that product development costs were reduced by up to 23.91% and productivity of barrels per day increased by around 150%. Also, power consumption is reduced by 100 KVA, CO_2 emissions by 1825.91 tons/year, water consumption by 96% and total electricity requirement is reduced to 25%. These results may improve the social, economic and environmental performance of the organizations.

9.3.3 Barrel manufacturing organization: Models and decisions frameworks

The research work observed that there are limited studies available for identifying and prioritizing key challenges for Indian manufacturing organizations. A combination of ANP and Fuzzy TOPSIS approach has been selected for the proposed research because a network model with dependence and feedback improves the rankings derived from decisions. The results indicate that organizational is the major challenge, while sustainable development challenge is the least prioritized. Data security and privacy, technological development and big data and analytics are the essential criteria while implementing Industry 4.0 and CE principles.

There are limited studies available related to circularity decisions in Industry 4.0 and CE. A framework for circularity decisions of Industry 4.0 and CE has been established with the help of GTMA. The findings of the study show that “Digitalization” is the most significant attribute while “Reduce” is the most optimum alternative to circularity. The findings of the research may be beneficial to researchers and managers in decision-making to ensure the smooth execution of Industry 4.0 to develop circularity in the manufacturing process.

The legal informatics research work observed that the present legal justice system does not address the legal and ethical issues of implementing legal informatics. Further, cybersecurity and data governance are the major issues while implementing these concepts. The government must seek to establish stronger jurisprudence to enable enterprises to protect data from the current cyber threats. It is recommended that companies become more proactive in terms of software and data security. Furthermore, legal technologies (legal tech Industry 4.0 technologies) reduced the communication gap between legal firms and clients. They provided sustainable as well as virtual collaborative solutions by allowing lawyers, such as prosecutors, counsellors, and advisors, to obtain information relevant to cases on which they are working together.

9.4 Major Research Contribution and Implications

To identify the various issues from the viewpoint of the Indian manufacturing industry with regards to Industry 4.0 and CE, the research work utilizes a number of approaches, including survey, case study, modelling and transition, and legal informatics frameworks. Based on the literature review and expert's opinions, the present research work addressed select issues of Industry 4.0 and CE, such as identifying and prioritizing key challenges, circularity index, circularity decisions, and framework for measuring the TBL performance of Industry 4.0 and CE. The major contributions and research implications of study are summarized as follows.

- Based on the detailed literature review, research gaps are identified, and research objectives are formulated. The research aimed to address the gaps in the literature. Academicians and researchers can use these knowledge gaps to advance their investigation of Industry 4.0 and CE.
- It is found from the literature review that there are a few studies on the adoption and implementation of Industry 4.0 and CE, particularly in manufacturing sector of emerging economies. Further, the present research work has considered only the Indian manufacturing

sector; however, the research could be applied to other developed and developing economies with marginal modifications. Therefore, as time passes, these analyses may consider the other sector such as healthcare, automobile, tyre recycling, food processing and textiles industries, etc.

- A questionnaire was established and a survey of the Indian manufacturing organization was carried out. The findings from study provide a significant understanding of the current challenges and issues in Industry 4.0 and CE, including select issues such as drivers, barriers, enablers, key challenges, circularity decisions, and triple bottom line performance of sustainability. These factors were identified and analyzed first time from the Indian manufacturing perspective. The results of the survey may assist industrialists and managers to have better insight into the Indian manufacturing industry. It may also develop a foundation for further investigation of the manufacturing industry. Hypotheses were established and integrated with the implementation of Industry 4.0 and CE factors, circularity decisions, and value engineering benefits and their correlation with TBL performance of Industry 4.0 and CE. The managers and industrialists may employ the findings of these hypotheses for identifying and analyzing these factors for enhancing their Industry 4.0 and CE performance. Researchers and practitioners can examine the other issues by referring to these individual models, which have been established for each of the issues.
- The research work article aims to implement value engineering and circular economy concepts and develop a cost-effective product with reduced power consumption, CO_2 emissions and minimum wastage of raw material. The research findings of this study may be useful for researchers and industrialists in implementing VE and CE concepts in each stage of product development, including inception, manufacturing, bidding and product implementation. The VE methodology may also offer real cost reduction opportunities and improve the functional efficiency of the product through the selection of material, machinery and manpower. Further, it may be useful to provide alternative designs or technologies for the manufacturing of products that are cost-effective, lightweight, and durable without

compromising the quality, while also promoting a triple bottom line of sustainability.

- A model of ANP and Fuzzy TOPSIS seeks to address the sustainable development characteristics of manufacturing processes, especially their value chains, by using Industry 4.0 and CE to facilitate industries in such circumstances. The research work discusses a statistical model and numerical findings to understand the pandemic effect better and formulate resilient and sustainable supply chain strategies. In such circumstances, managers and industrialists need to consider the sustainable development perspective in manufacturing industries while adopting the modern technologies of Industry 4.0 and CE for sustainable development. The study may guide academic researchers and supply chain partners in decision-making to limit the disruption of the pandemic in developing economies. The main challenge that organizations need to focus on the sustainable development to manage the impact of the pandemic. Adapting to challenges and developing valuable decision-making skills to make effective decisions are substantiated pathways for organizations looking to improve their environmental sustainability.
- The proposed research identified and analyzed various circularity attributes of Industry 4.0 and CE by using GTMA. The results of the study be beneficial to academicians and researchers in strategic decision-making for achieving circularity decisions in their organizations. This research seeks to address the sustainable development characteristics of manufacturing processes, especially their value chains, by using Industry 4.0 and CE to facilitate industries in such circumstances. The study discusses a statistical model and numerical findings to understand the pandemic effect better and formulate resilient and sustainable supply chain strategies. In such circumstances, managers and industrialists need to consider the sustainable development perspective in manufacturing industries while adopting the modern technologies of Industry 4.0 and CE for sustainable development.

9.5 Recommendations of the Study

This study's investigation and analysis provided valuable information about where the Indian manufacturing industry may need to improve. Although issues and challenges can vary widely from business to business based on a wide range of variables like goods, target audiences, and the competitive landscape, it can be helpful for practitioners to review a synthesis of certain key recommendations. The following are a couple of recommendations made by the research to help the Indian manufacturing industry.

- It is found that Industry 4.0 and CE select issues and challenges can also be analyzed through other statistical as well as MCDM techniques, including VIKOR, Fuzzy ISM, Mixed Integral Method and Markovian. Fourier bootstrap Toda-Yamamoto and t-test can also be performed based on an adequate number of responses collected through questionnaire development for statistical validation of the qualitative frameworks of Industry 4.0 and CE select issues and challenges.
- Industries should explore the formation of a cooperative collaboration mainly in recycling/redesigning/remanufacturing of products, which necessitates a large investment in machinery and for which a large output is anticipated. Industries should plan their waste management and use product recovery systems by using effective Industry 4.0 and CE implementation to be in compliance with the waste management standards and regulations of 2016 and 2019.
- The successful implementation of Industry 4.0 and CE is significant for managing uncertainties in the present Indian manufacturing industry. Industries could anticipate the influence of Industry 4.0 and CE on their industry and adjust their strategies accordingly.
- Industries should consider circularity decisions as strategic concerns and the significant factors at suitable places must take circularity decisions.
- Industries must consider the triple bottom line perspective of sustainability when making circularity decisions. The study suggests using GTMA for circularity decisions in Industry 4.0

and CE. This will support industries to ensure their contribution towards sustainable development even if they implement Industry 4.0 and CE approaches.

- The study has established a framework for assessing the triple bottom line performance of Industry 4.0 and CE, and it has incorporated the concept of long-term sustainability into these practices. The proposed methodology of VE and CE and cleaner production can be further extended with CO2 constraint to control CO_2 emissions due to production, holding, and transportation of each unit through carriers considering economic and sustainable features. In addition to carbon cap and trade, other carbon regulating policies, such as a strict carbon cap and strict tax can be incorporated, and their effectiveness can be compared.

- According to the Indian government, several benefits are possible from the "Made in India", “Digital India”, and “Udyog Bharat 4.0” initiatives. Industries need to keep an eye on this trend and may look into domestic production and recycling/remanufacturing/redesigning as an alternative to relying on foreign imports.

9.6 Limitations and Future Research Directions

Each academic study comes with its own set of advantages and limitations. The research itself has its own limitations. The following section addresses the limitations of the study and offers recommendations for future research.

- A survey method was used for the generalization of findings, however this was limited by a low response rate and a relatively small sample size. In future studies, a larger sample size may benefit from a higher response rate if the sample size is increased. However, if the measurement model was found to be statistically appropriate for the SEM, a larger sample size might be utilized to increase the results' significance and credibility. Hypotheses were developed related to adoption and implementation factors, value engineering, and circularity decisions, and their association with the performance of Industry 4.0 and CE. Even though individual models have been established, more factors can be explored when developing hypotheses, and their association with Industry 4.0 and CE performance can be tested by employing the methods employed here. The future of evaluating the impact of several challenges on Industry 4.0 and CE performance may lie in their consolidation.

- In CE and VE performance measure framework, one of the limitations of the present study is that only the triple bottom line performance of the CE has been considered for the investigation. In future research, other performance parameters, such as customer satisfaction and CSR may also be examined in depth. Moreover, there is an opportunity to investigate the relationship between individual decision strategies and sustainable performance in the future. The study was limited to Indian manufacturing organizations however, in the future similar studies may be conducted in different industries in different countries. Furthermore, combining VE implementation with Industry 4.0-based technologies may be beneficial for long-term performance in the future industry. These technologies can provide real-time information on the product development processes and identify failures and errors, which may help to reduce breakdowns in the production processes.
- The ANP Fuzzy TOPSIS technique has been applied for the identification and prioritization of key challenges from the Indian manufacturing organization. The present study has a couple of limitations. The number of experts considered in the analysis is limited. Further, this study has considered only the Indian manufacturing sector; however, the research could be applied to other developed and developing economies with marginal modifications. Therefore, as time passes, these analyses may consider the other sector such as healthcare, automobile, tyre recycling, food processing and textiles industries, etc. The authors have considered five challenges and fifteen criteria for implementing Industry 4.0 technologies during the pandemic in order to develop a circular supply chain. Future researchers could explore other factors affecting this implementation, such as legal and ethical effects, human-machine collaboration, and sustainable effects, etc. In addition, the identified challenges can be investigated further in future research to determine their causal and dependent relations.

The present study has used a combination of ANP and fuzzy TOPSIS approaches; as time passes, future research could be compared these approaches with other MCDM approaches, which may suggest the best method to consider these factors. In future research, sensitivity analysis may also be conducted. Finally, organizations must design and develop circular business models to deal with managerial and environmental disruptions due to the pandemic using Industry 4.0 applications.

- GTMA has been used to establish the network in accordance with a predetermined strategy, and it serves as the basis for circularity decisions in CE and Industry 4.0. This approach could be used in future studies to establish more frameworks for various Industry 4.0 and CE applications in various real-world environments. On the other hand, methodologies, are sufficiently adaptable to incorporate a variety of strategies and may be tailored to take into consideration a wide range of qualitative and quantitative factors. The study also included a few limitations due to the fact that it considered a group of four experts. In order to avoid extrapolating findings and recommendations, future studies may take into account a larger group of experts, enabling the development of more case studies. A scale with a fuzzy base can be used to avoid ambiguity and prevent the possibility of bias. It is possible to determine their causal and dependent relationships by using the established circularity alternatives.
- The legal informatics framework has a couple of limitations. Firstly, the present study has considered only a theoretical perspective for developing the framework. A quantitative decision-making model can be utilized in future studies to validate the findings. Secondly, the identified issues may be explored further in future research to evaluate their causal and dependent relationships. The sensitivity analysis may also be conducted for sustainable legal informatics modelling.

9.7 Concluding Remarks

The major findings of this research work may contribute significantly to addressing various issues and challenges related to Industry 4.0 and CE from the Indian viewpoint. The study was conducted in the Indian manufacturing organization in a period when the development of “Make in India”, “Digital India”, “Udyog Bharat 4.0”, “waste management rules and regulations”, and further actions transformed the movements of the Indian manufacturing industry. Competitive pressures and convenient payment methods such as cash on delivery have resulted in more generous return policies. Organizations in India are being forced to reevaluate their approaches to managing end-of-life product returns due to the introduction of regulations such as the Waste Management Society of India and the National Manufacturing Policy. Several organizations are making preparations for the introduction of Industry 4.0 and CE by restructuring their supply networks. The study identified and prioritized key challenges for the implementation of Industry 4.0 and CE in the Indian manufacturing industry. These factors provided useful information on Industry 4.0 and CE in the Indian manufacturing industry and may provide direction to the industrialist and researchers for the implementation of Industry 4.0 and CE. The study mainly focused on select issues and investigated those issues by survey method, case study, and recommended solutions by establishing frameworks and models. The research work observed that performance measures and circularity decisions are positively associated with triple bottom line performance of Industry 4.0 and CE. A value engineering and CE framework have been established to measure the triple bottom performance of manufacturing industry. This research work mainly focused triple bottom line performance to analyze the contribution of Industry 4.0 and CE in sustainability efforts of an organization. It is recommended by the Government of India's CSR strategy for 2019 that industries contribute one percent of their profits to social and environmental concerns. Organizations may implement sustainable development-related perspectives in the performance measurement of Industry 4.0 and CE and can contribute some portion of CSR funds to the Industry 4.0 and CE. The research work established transitional as well as conceptual frameworks, and statistical models, which may help in improving the triple bottom line performance of Industry 4.0 and CE. The findings of this thesis may help academicians, researchers, and practitioners in their future research work. The results of the findings may also benefit the industrialists and manager managers in developing, implementing and functioning the Industry 4.0 and CE system effectively and efficiently.

REFERENCES

1. Abraham, R., Schneider, J., and Vom Brocke, J. (2019). Data governance: A conceptual framework, structured review, and research agenda. *International Journal of Information Management*, *49*, 424-438.
2. Abdul-Hamid, A. Q., Ali, M. H., Tseng, M. L., Lan, S., and Kumar, M. (2020). Impeding challenges on industry 4.0 in circular economy: Palm oil industry in Malaysia. *Computers and Operations Research*, *123*, 105052.
3. Aceto, G., Persico, V., and Pescapé, A. (2020). Industry 4.0 and health: Internet of things, big data, and cloud computing for healthcare 4.0. *Journal of Industrial Information Integration*, *18*, 100129.
4. Agrawal, S., Singh, R. K., and Murtaza, Q. (2018). Reverse supply chain issues in Indian electronics industry: a case study. *Journal of Remanufacturing*, *8*, 115-129.
5. Agrawal, S., and Singh, R. K. (2019). Analyzing disposition decisions for sustainable reverse logistics: Triple Bottom Line approach. *Resources, Conservation and Recycling*, *150*, 104448.
6. Agyemang, M., Kusi-Sarpong, S., Khan, S. A., Mani, V., Rehman, S. T., and Kusi-Sarpong, H. (2019). Drivers and barriers to circular economy implementation: An explorative study in Pakistan's automobile industry. *Management Decision*, 57 (4), 971-994.

7. Akinade, O. O., and Oyedele, L. O. (2019). Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS). *Journal of Cleaner Production*, *229*, 863-873.

8. Alcácer, V., and Cruz-Machado, V. (2019). Scanning the industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology, an International Journal*, *22*(3), 899-919.

9. Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., and Ayyash, M. (2015). Internet of things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys and Tutorials*, *17*(4), 2347-2376.

10. Ancarani, A., Di Mauro, C., and Mascali, F. (2019). Backshoring strategy and the adoption of Industry 4.0: Evidence from Europe. *Journal of World Business*, *54*(4), 360-371.

11. Antikainen, M., Uusitalo, T., and Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. *Procedia Cirp*, *73*, 45-49.

12. Babiceanu, R. F., and Seker, R. (2016). Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. *Computers in Industry*, *81*, 128-137.

13. Badri, A., Boudreau-Trudel, B., and Souissi, A. S. (2018). Occupational health and safety in the industry 4.0 era: A cause for major concern?. *Safety Science*, *109*, 403-411.

14. Bag, S., Wood, L. C., Mangla, S. K., and Luthra, S. (2020a). Procurement 4.0 and its implications on business process performance in a circular economy. *Resources, Conservation and Recycling*, *152*, 104502.

15. Bag, S., Yadav, G., Wood, L. C., Dhamija, P., and Joshi, S. (2020b). Industry 4.0 and the circular economy: Resource melioration in logistics. *Resources Policy*, *68*, 101776.

16. Bag, S., and 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.

17. Bai, C., Fahimnia, B., and Sarkis, J. (2017). Sustainable transport fleet appraisal using a hybrid multi-objective decision making approach. *Annals of Operations Research*, *250*(2), 309-340.
18. Bechtel, N., Bojko, R., and Völkel, R. (2013). Be in the loop: circular economy and strategic sustainable development.
19. Bocken, N. M., Olivetti, E. A., Cullen, J. M., Potting, J., and Lifset, R. (2017). Taking the circularity to the next level: a special issue on the circular economy. *Journal of Industrial Ecology*, *21*(3), 476-482.
20. Bodrow, W. (2017). Impact of Industry 4.0 in service oriented firm. *Advances in Manufacturing*, *5*(4), 394-400.
21. Borgia, E. (2014). The Internet of Things vision: Key features, applications and open issues. *Computer Communications*, *54*, 1-31.
22. Caldera, H. T. S., Desha, C., and Dawes, L. (2019). Evaluating the enablers and barriers for successful implementation of sustainable business practice in 'lean'SMEs. *Journal of Cleaner Production*, *218*, 575-590.
23. Castelo-Branco, I., Cruz-Jesus, F., and Oliveira, T. (2019). Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. *Computers in Industry*, *107*, 22-32.
24. Chen, S. J. and Hwang, C. L. (1992). Fuzzy multiple attribute decision making methods. *Springer, Berlin, Heidelberg*, 289-486.
25. Centobelli, P., Cerchione, R., and Ertz, M. (2020). Managing supply chain resilience to pursue business and environmental strategies. *Business Strategy and the Environment*, *29*(3), 1215-1246.
26. Cetrulo, A. and Nuvolari, A. (2020). Recent technological trends and their impact on labour, *Journal of Industrial and Business Economics*, 0123456789, 40812.

27. Charro, A., and Schaefer, D. (2018). Cloud Manufacturing as a new type of Product-Service System. *International Journal of Computer Integrated Manufacturing*, *31*(10), 1018-1033.

28. Chauhan, C., Sharma, A., and Singh, A. (2019). A SAP-LAP linkages framework for integrating Industry 4.0 and circular economy. *Benchmarking: An International Journal*, *28*(5), 1638-1664.

29. Chauhan, C., Parida, V., and Dhir, A. (2022). Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change*, *177*, 121508.

30. Chin, W. W. (1998). The partial least squares approach to structural equation modeling. *Modern Methods for Business Research*, *295*(2), 295-336.

31. Cooper, R., Slagmulder, R. (2017). Target costing and value engineering. Routledge.

32. Contissa, G., Godano, F., and Sartor, G. (2021). Computation, Cybernetics and the Law at the Origins of Legal Informatics. *Italian Philosophy of Technology: Socio-Cultural, Legal, Scientific and Aesthetic Perspectives on Technology*, 91-110.

33. da Silva, F. S. T., da Costa, C. A., Crovato, C. D. P., and da Rosa Righi, R. (2020). Looking at energy through the lens of Industry 4.0: A systematic literature review of concerns and challenges. *Computers and Industrial Engineering*, *143*, 106426.

34. Dachs, B., Kinkel, S., and Jäger, A. (2019). Bringing it all back home? Backshoring of manufacturing activities and the adoption of Industry 4.0 technologies. *Journal of World Business*, *54*(6), 101017.

35. de Abreu, M. C. S., and Ceglia, D. (2018). On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis. *Resources, Conservation and Recycling*, *138*, 99-109.

36. De Jesus, A., and Mendonça, S. (2018). Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. *Ecological Economics*, *145*, 75-89.

37. De Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., and Godinho Filho, M. (2018). When titans meet–Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting and Social Change*, *132*, 18-25.

38. Demeter, K., and Losonci, D. (2019). Transferring lean knowledge within multinational networks. *Production Planning and Control*, *30*(2-3), 211-224.

39. Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., and Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75-84.

40. Dev, N. K., Shankar, R., and Qaiser, F. H. (2020). Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resources, Conservation and Recycling*, *153*, 104583.

41. Diaz, A., Schöggl, J. P., Reyes, T., and Baumgartner, R. J. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. *Sustainable Production and Consumption*, *26*, 1031-1045.

42. Díaz-Chao, Á., Ficapal-Cusí, P., and Torrent-Sellens, J. (2021). Environmental assets, industry 4.0 technologies and firm performance in Spain: A dynamic capabilities path to reward sustainability. *Journal of Cleaner Production*, *281*, 125264.

43. Dubey, R., Gunasekaran, A., Childe, S. J., Papadopoulos, T., and Helo, P. (2018). Supplier relationship management for circular economy: influence of external pressures and top management commitment. *Management Decision*, *57*(4), 767-790.

44. Ellen MacArthur Foundation (2013). Towards the circular economy, economic and business rationale for an accelerated transition. Ellen MacArthur Foundation: Cowes, UK.

45. Ellen MacArthur Foundation (2017). Priority Research Agenda. Available at.

https://www.ellenmacarthurfoundation.org/assets/downloads/higher-education/EMF_ Priority-Research-Agenda- copy.pdf.

46. Elmogahzy, Y. E. (2019). *Engineering textiles: Integrating the design and manufacture of textile products*. Woodhead Publishing.
47. Eltantawy, R. A., Fox, G. L., and Giunipero, L. (2009). Supply management ethical responsibility: reputation and performance impacts. *Supply Chain Management: An International Journal*, 14(2), 99-108.
48. Easterby-Smith, Thorpe, M. and Lowe,R., A. (2002). Management Research-An Introduction, *London: SAGE Publications Ltd*.
49. Falk, R. F., and Miller, N. B. (1992). A primer for soft modeling. University of Akron Press.
50. Ferrell, O. C., Rogers, M. M., Ferrell, L., and Sawayda, J. (2013). A framework for understanding ethical supply chain decision making. *Journal of Marketing Channels*, *20*(3-4), 260-287.
51. Flores, C.C., Bressers, H., Gutierrez, C. and de Boer, C., (2018), "Towards circular economy–a wastewater treatment perspective, the Presa Guadalupe case", *Management Research Review*, 41(5), 554-571.
52. Fornell, C., and Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research*, *18*(1), 39-50.
53. Garcia-Muiña, F. E., González-Sánchez, R., Ferrari, A. M., and Settembre-Blundo, D. (2018). The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company. *Social Sciences*, *7*(12), 255.
54. Geissdoerfer, M., Savaget, P., Bocken, N. M., and Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. *Journal of Cleaner Production*, *143*, 757-

768.

55. Geisser, S. (1974). A predictive approach to the random effect model. *Biometrika*, *61*(1), 101-107.

56. Genovese, A., Acquaye, A. A., Figueroa, A., and Koh, S. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, 344-357.

57. George, D. A., Lin, B. C. A., and Chen, Y. (2015). A circular economy model of economic growth. *Environmental Modelling and Software*, *73*, 60-63.

58. Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11-32.

59. Ghobakhloo, M. (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of manufacturing technology management, 29(6),910-936.*

60. Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869.

61. Gölzer, P., Cato, P., and Amberg, M. (2015). Data processing requirements of industry 4.0-use cases for big data applications, *European Conference on Information Systems*, 1–13.

62. Gómez, A. M. M., González, F. A., and Bárcena, M. M. (2018). Smart eco-industrial parks: A circular economy implementation based on industrial metabolism. *Resources, Conservation and Recycling*, *135*, 58-69.

63. Gonzalez-Padron, T. L. (2016). Ethics in the supply chain: Follow-up processes to audit results. *Journal of Marketing Channels*, *23*(1-2), 22-33.

64. Gusmerotti, N. M., Testa, F., Corsini, F., Pretner, G., and Iraldo, F. (2019). Drivers and approaches to the circular economy in manufacturing firms. *Journal of Cleaner Production*, *230*, 314-327.

65. Hair, J. F. J., Black, W. C., Babin, B. J., Anderson, R. E., and Tatham, R. (2010). Multivariate data analysis upper saddle river: pearson prentice hall. *Links*.

66. Hanna, M. D., Newman, W. R., and Johnson, P. (2000). Linking operational and environmental improvement through employee involvement. *International Journal of Operations and Production Management*, 20 (2), 148–165.

67. Hart, J., Adams, K., Giesekam, J., Tingley, D. D., and Pomponi, F. (2019). Barriers and drivers in a circular economy: the case of the built environment. *Procedia Cirp*, *80*, 619-624.

68. Hermann, M., Pentek, T., and Otto, B. (2016). Design principles for industrie 4.0 scenarios. *Hawaii international conference on system sciences (HICSS)*, IEEE, 3928-3937..

69. Herndon, N. (2005). Effective ethical response: A new approach to meeting channel stakeholder needs for ethical behavior and socially responsible conduct. *Journal of Marketing Channels*, *13*(1), 63-78.

70. Henseler, J., Ringle, C. M., and Sinkovics, R. R. (2009). The use of partial least squares path modeling in international marketing. *Advances in International Marketing, 20,* 277-319.

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

72. Horváth, D., and Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?. *Technological Forecasting and Social Change*, *146*, 119-132.

73. Hussain, M., and Malik, M. (2020). Organizational enablers for circular economy in the context of sustainable supply chain management. *Journal of Cleaner Production*, *256,* 120375.

74. Iacobucci, D. (2010). Structural equations modeling: Fit indices, sample size, and

advanced topics. *Journal of Consumer Psychology*, *20*(1), 90-98.

75. Ilić, M., and Nikolić, M. (2016). Drivers for development of circular economy–A case study of Serbia. *Habitat International*, *56*, 191-200.
76. Jabbour, C. J. C., Fiorini, P. D. C., Wong, C. W., Jugend, D., Jabbour, A. B. L. D. S., Seles, B. M. R. P. and da Silva, H. M. R. (2020). First-mover firms in the transition towards the sharing economy in metallic natural resource-intensive industries: Implications for the circular economy and emerging industry 4.0 technologies. *Resources Policy*, *66*, 101596.
77. Jabbour, C. J. C., De Sousa Jabbour, A. B. L., Sarkis, J., and Godinho Filho, M. (2019). Unlocking the circular economy through new business models based on large-scale data: an integrative framework and research agenda. *Technological Forecasting and Social Change*, *144*, 546-552.
78. Jaeger, B. and Upadhyay, A., (2020), "Understanding barriers to circular economy: cases from the manufacturing industry", *Journal of Enterprise Information Management*, *33*(4), 729-745.
79. Jindal, A., and Sangwan, K. S. (2013). Development of an interpretive structural model of drivers for reverse logistics implementation in Indian industry. *International Journal of Business Performance and Supply Chain Modelling*, *5*(4), 325-342.
80. Kalmykova, Y., Sadagopan, M., and Rosado, L. (2018). Circular economy–From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190-201.
81. Kamble, S. S., Gunasekaran, A., and Sharma, R. (2018a). Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. *Computers in Industry*, *101*, 107-119.
82. Kamble, S. S., Gunasekaran, A., and Gawankar, S. A. (2018b). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future

perspectives. *Process Safety and Environmental Protection*, *117*, 408-425.

83. Kamigaki, T. (2017). Object-oriented RFID with IoT: a design concept of information systems in manufacturing. *Electronics*, *6*(1), 14.

84. Kelloway, E. K., and Barling, J. (2000). Knowledge work as organizational behavior. *International Journal of Management Reviews*, *2*(3), 287-304.

85. Khan, I. S., Ahmad, M. O., and Majava, J. (2021a). Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives. *Journal of Cleaner Production*, *297*, 126655.

86. Khan, S. A. R., Razzaq, A., Yu, Z., and Miller, S. (2021b). Industry 4.0 and circular economy practices: A new era business strategies for environmental sustainability. *Business Strategy and the Environment*, *30*(8), 4001-4014.

87. Kiraz, A., Canpolat, O., Özkurt, C., and Taşkın, H. (2020). Analysis of the factors affecting the Industry 4.0 tendency with the structural equation model and an application. *Computers and Industrial Engineering*, *150*, 106911.

88. Kirchherr, J., Reike, D., and Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221-232.

89. Kirchherr, J., and Piscicelli, L. (2019). Towards an education for the circular economy (ECE): five teaching principles and a case study. *Resources, Conservation and Recycling*, *150*, 104406.

90. Kitchenham, B. (2004). Procedures for performing systematic reviews. *Keele, UK, Keele University*, *33*(2004), 1-26.

91. Koch, V., Kuge, S., Geissbauer, R., and Schrauf, S. (2014). Industry 4.0: Opportunities and challenges of the industrial internet. *Strategy and PwC*, 5-50.

92. Köchling, A. (2003). Human resources management under conditions of demographic change. Ageing and work in Europe: strategies at company level and public policies in selected European countries. *Stuttgart: IRB*, 99–106.

93. Kouhizadeh, M., Zhu, Q., and Sarkis, J. (2020). Blockchain and the circular economy: potential tensions and critical reflections from practice. *Production Planning and Control*, *31*(11-12), 950-966.

94. Kristoffersen, E., Blomsma, F., Mikalef, P., and Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of business research*, *120*, 241-261.

95. Kshetri, N. (2018). 1 Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management*, *39*, 80-89.

96. Kumar, R., Singh, R. K., and Dwivedi, Y. K. (2020a). Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *Journal of Cleaner Production*, *275*, 124063.

97. Kumar, M. S., Raut, R. D., Narwane, V. S., and Narkhede, B. E. (2020b). Applications of industry 4.0 to overcome the COVID-19 operational challenges. *Diabetes and Metabolic Syndrome: Clinical Research and Reviews*, *14*(5), 1283-1289.

98. Kumar, P., Singh, R. K., and Kumar, V. (2021). Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers. *Resources, Conservation and Recycling*, *164*, 105215.

99. Kuo, C. C., Shyu, J. Z., and Ding, K. (2019). Industrial revitalization via industry 4.0–A comparative policy analysis among China, Germany and the USA. *Global transitions*, *1*, 3-14.

100. Kurt, R. (2019). Industry 4.0 in terms of industrial relations and its impacts on labour life. *Procedia Computer Science*, *158*, 590-601.

101. Lasi, H., Fettke, P., Kemper, H. G., Feld, T., and Hoffmann, M. (2014). Industry 4.0. *Business and Information Systems Engineering*, *6*(4), 239-242.

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

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

104. Lezzi, M., Lazoi, M., and Corallo, A. (2018). Cybersecurity for Industry 4.0 in the current literature: A reference framework. *Computers in Industry*, *103*, 97-110.

105. Li, Y., Dai, J., and Cui, L. (2020). The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model. *International Journal of Production Economics*, *229*, 107777.

106. Liao, Y., Deschamps, F., Loures, E. D. F. R., and Ramos, L. F. P. (2017). Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609-3629.

107. Lieder, M., and Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36-51.

108. Lomotey, R. K., Pry, J. C., and Chai, C. (2018). Traceability and visual analytics for the Internet-of-Things (IoT) architecture. *World Wide Web*, *21*(1), 7-32.

109. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of industrial information integration*, *6*, 1-10.

110. Luthra, S., and Mangla, S. K. (2018). Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Safety and Environmental Protection*, *117*, 168-179.

111. MacDougall, W. (2014). Industrie 4.0: Smart manufacturing for the future. Germany Trade and Invest.

112. Machado, C. G., Winroth, M. P., and Ribeiro da Silva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: an emerging research agenda. *International Journal of Production Research*, *58*(5), 1462-1484.

113. Mangla, S. K., Luthra, S., Mishra, N., Singh, A., Rana, N. P., Dora, M., and Dwivedi, Y. (2018). Barriers to effective circular supply chain management in a developing country context. *Production Planning and Control*, *29*(6), 551-569.

114. Mayring, P., 2003. Qualitative in halts analyse (Qualitative content analysis). *Qualitative Forschung Ein Handbuch (Qualitative Research: A Handbook)*, 468-475.

115. Mital, A., and Pennathur, A. (2004). Advanced technologies and humans in manufacturing workplaces: an interdependent relationship. *International Journal of Industrial Ergonomics*, *33*(4), 295-313.

116. Moktadir, M. A., Rahman, T., Rahman, M. H., Ali, S. M., and Paul, S. K. (2018a). Drivers to sustainable manufacturing practices and circular economy: A perspective of leather industries in Bangladesh. *Journal of Cleaner Production*, *174*, 1366-1380.

117. Moktadir, M. A., Ali, S. M., Kusi-Sarpong, S., and Shaikh, M. A. A. (2018b). Assessing challenges for implementing Industry 4.0: Implications for process safety and environmental protection. *Process Safety and Environmental Protection*, *117*, 730-741.

118. Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., and Dewulf, J. (2019). Circular economy indicators: What do they measure?. *Resources, Conservation and Recycling*, *146*, 452-461.

119. Muhuri, P. K., Shukla, A. K., and Abraham, A. (2019). Industry 4.0: A bibliometric analysis and detailed overview. *Engineering Applications of Artificial Intelligence*, *78*, 218-235.

120. Müller, J. M., Buliga, O., and Voigt, K. I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. *Technological Forecasting and Social Change*, *132*, 2-17.

121. Murray, A., Skene, K., and Haynes, K. (2017). The circular economy: an interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics*, *140*(3), 369-380.

122. Mutingi, M. (2013). Developing green supply chain management strategies: A taxonomic approach. *Journal of Industrial Engineering and Management*, *6*(2), 525-546.

123. Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., and Tortorella, G. (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*, *30*(3), 607-627.

124. Ngan, S. L., How, B. S., Teng, S. Y., Promentilla, M. A. B., Yatim, P., Er, A. C., and Lam, H. L. (2019). Prioritization of sustainability indicators for promoting the circular economy: The case of developing countries. *Renewable and Sustainable Energy Reviews*, *111*, 314-331.

125. Nordin, N., Ashari, H., and Hassan, M. G. (2014). Drivers and barriers in sustainable manufacturing implementation in Malaysian manufacturing firms. *IEEE International Conference on Industrial Engineering and Engineering Management*, 687-691.

126. Nunnally, J. C., and Bernstein, I. H. (1978). Psychometric theory mcgraw-hill new york. *The role of university in the development of entrepreneurial vocations: a Spanish study*, 387-405.

127. Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., and Tiwari, A. (2018). Data-driven approaches for circular economy in manufacturing for digital technologies: a review of current research and proposed framework, 2018080159.

128. Ozkan-Ozen, Y. D., Kazancoglu, Y., and Mangla, S. K. (2020). Synchronized barriers for circular supply chains in industry 3.5/industry 4.0 transition for sustainable resource management. *Resources, Conservation and Recycling*, *161*, 104986.

129. Oztemel, E., and Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*(1), 127-182.

130. Park, J. Y., and Chertow, M. R. (2014). Establishing and testing the “reuse potential” indicator for managing wastes as resources. *Journal of Environmental Management*, *137*,

45-53.

131. Patyal, V. S., Sarma, P. R. S., Modgil, S., Nag, T., and Dennehy, D. (2022). Mapping the links between Industry 4.0, circular economy and sustainability: A systematic literature review. *Journal of Enterprise Information Management*, *35*(1), 1-35.

132. Pieroni, M. P., McAloone, T. C., and Pigosso, D. C. (2019). Business model innovation for circular economy and sustainability: A review of approaches. *Journal of Cleaner Production*, *215*, 198-216.

133. Queiroz, M. M., and Wamba, S. F. (2019). Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA. *International Journal of Information Management*, *46*, 70-82.

134. Radanliev, P., De Roure, D. C., Nicolescu, R., Huth, M., Montalvo, R. M., Cannady, S., and Burnap, P. (2018). Future developments in cyber risk assessment for the internet of things. *Computers in Industry*, *102*, 14-22.

135. Raj, A., Dwivedi, G., Sharma, A., De Sousa Jabbour, A. B. L., and 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*, 107546.

136. Rajput, S., and Singh, S. P. (2019). Connecting circular economy and industry 4.0. *International Journal of Information Management*, *49*, 98-113.

137. Rajput, S., and Singh, S. P. (2019). Industry 4.0− challenges to implement circular economy. *Benchmarking: An International Journal*.

138. Rajput, S., and Singh, S. P. (2020). Industry 4.0 Model for circular economy and cleaner production. *Journal of Cleaner Production*, *277*, 123853.

139. Rahman, M., Kamal, M. M., Aydin, E., and Haque, A. U. (2022). Impact of Industry 4.0 drivers on the performance of the service sector: comparative study of cargo logistic firms in developed and developing regions. *Production Planning and Control*, *33*(2-3),

228-243.

140. Rauch, E., Linder, C., and Dallasega, P. (2020). Anthropocentric perspective of production before and within Industry 4.0. *Computers and Industrial Engineering*, *139*, 105644.

141. Reche, A. Y. U., Junior, O. C., Estorilio, C. C. A., and Rudek, M. (2020). Integrated product development process and green supply chain management: Contributions, limitations and applications. *Journal of Cleaner Production*, *249*, 119429.

142. Reischauer, G. (2018). Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing. *Technological Forecasting and Social Change*, *132*, 26-33.

143. Reyes, P. M., Worthington, W. J., and Collins, J. D. (2015). Knowledge management enterprise and RFID systems: Adoption to supply chain performance. *Management Research Review*.

144. Rizos, V., Behrens, A., Van der Gaast, W., Hofman, E., Ioannou, A., Kafyeke, T., ... and Topi, C. (2016). Implementation of circular economy business models by small and medium-sized enterprises (SMEs): Barriers and enablers. *Sustainability*, *8*(11), 1212.

145. Saaty, T. L. (1996). *Decision making with dependence and feedback: The analytic network process* (Vol. 4922, No. 2). Pittsburgh: RWS publications.

146. Sahu, A., Agrawal, S., and Kumar, G. (2022). Integrating Industry 4.0 and circular economy: a review. *Journal of Enterprise Information Management*, 35(3), 885-917, 2022.

147. Sahu, A., Agrawal, S., and Kumar, G. (2023a). Triple bottom line performance of manufacturing Industry: A value engineering approach. *Sustainable Energy Technologies and Assessments*, *56*, 103029.

148. Sahu, A., Agrawal, S., and Kumar, G. (2023b). Challenges of Implementing Industry 4.0 in Achieving Sustainable Development Goals: A Case of Indian Manufacturing

Organization. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*.

149. Saleem, H., Li, Y., Ali, Z., Ayyoub, M., Wang, Y., and Mehreen, A. (2020). Big data use and its outcomes in supply chain context: the roles of information sharing and technological innovation. *Journal of Enterprise Information Management*, 34(4), 1121-1143.

150. Sauvé, S., Bernard, S., and Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development, 17*, 48-56.

151. Schneider, P. (2018). Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. *Review of Managerial Science, 12*(3), 803-848.

152. Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., and Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production, 207*, 542-559.

153. Shen, Q. (1993). *A knowledge based structure for implementing Value Management in the design of office buildings*. University of Salford (United Kingdom), 360.

154. Sehnem, S., Campos, L. M., Julkovski, D. J., and Cazella, C. F. (2019). Circular business models: level of maturity. *Management Decision*, 57 (4), 1043-1066.

155. Setti, P. H. P., Junior, O. C., and Estorilio, C. C. A. (2021). Integrated product development method based on Value Engineering and design for assembly concepts. *Journal of Industrial Information Integration, 21*, 100199.

156. Sevigné-Itoiz, E., Gasol, C. M., Rieradevall, J., and Gabarrell, X. (2014). Environmental consequences of recycling aluminum old scrap in a global market. *Resources, Conservation and Recycling, 89*, 94-103.

157. Sharma, S., Tim, U. S., Wong, J., Gadia, S., and Sharma, S. (2014). A brief review on leading big data models. *Data Science Journal*, 14-041.

158. Sharma, S. (2016). Expanded cloud plumes hiding Big Data ecosystem. *Future Generation Computer Systems, 59*, 63-92.

159. Sharma, S., Chang, V., Tim, U. S., Wong, J., and Gadia, S. (2019). Cloud and IoT-based emerging services systems. *Cluster Computing*, *22*, 71-91.
160. Sharma, S., and AL, R. S. (2021). eLegalls: Enriching a Legal Justice System in the Emerging Legal Informatics and Legal Tech Era. *International Journal of Legal Information*, *49*(1), 16-31.
161. Singhal, D., Tripathy, S., and Jena, S. K. (2019). Acceptance of remanufactured products in the circular economy: an empirical study in India. *Management Decision*, 57 (4), 953 970.
162. Sivarajah, U., Kamal, M. M., Irani, Z., and Weerakkody, V. (2017). Critical analysis of Big Data challenges and analytical methods. *Journal of Business Research*, *70*, 263-286.
163. Soualhia, M., Khomh, F., and Tahar, S. (2017). Task scheduling in big data platforms: a systematic literature review. *Journal of Systems and Software*, *134*, 170-189.
164. Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., and Haug, A. (2021). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. *Production Planning and Control*, *32*(10), 811-828.
165. Su, B., Heshmati, A., Geng, Y., and Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215-227.
166. Tam, E., Soulliere, K., and Sawyer-Beaulieu, S. (2019). Managing complex products to support the circular economy. *Resources, Conservation and Recycling*, *145*, 124-125.
167. Tao, F., Qi, Q., Wang, L., and Nee, A. Y. C. (2019). Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. *Engineering*, *5*(4), 653-661.
168. Thames, L., and Schaefer, D. (2017). Industry 4.0: an overview of key benefits, technologies, and challenges. *Cybersecurity for Industry 4.0*, 1-33.
169. Thun, J. H., Größler, A., and Miczka, S. (2007). The impact of the demographic

transition on manufacturing: Effects of an ageing workforce in German industrial firms. *Journal of Manufacturing Technology Management*, 18 (8), 985-999.

170. Tranfield, D., Denyer, D., and Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, *14*(3), 207-222.

171. Tseng, M. L., Tan, R. R., Chiu, A. S., Chien, C. F., and Kuo, T. C. (2018). Circular economy meets industry 4.0: Can big data drive industrial symbiosis?. *Resources, Conservation and Recycling*, *131*, 146-147.

172. Tseng, M. L., Chiu, A. S., Liu, G., and Jantaralolica, T. (2020). Circular economy enables sustainable consumption and production in multi-level supply chain system. *Resources, Conservation and Recycling*, *154*, 104601.

173. Tyagi, S., Choudhary, A., Cai, X., and Yang, K. (2015). Value stream mapping to reduce the lead-time of a product development process. *International Journal of Production Economics*, *160*, 202-212.

174. Urciuoli, L., Hintsa, J., and Ahokas, J. (2013). Drivers and barriers affecting usage of e-Customs—A global survey with customs administrations using multivariate analysis techniques. *Government Information Quarterly*, *30*(4), 473-485.

175. Vaidya, S., Ambad, P., and Bhosle, S. (2018). Industry 4.0–a glimpse. *Procedia Manufacturing*, *20*, 233-238.

176. Vinzi, V. E., Trinchera, L., and Amato, S. (2010). PLS path modeling: from foundations to recent developments and open issues for model assessment and improvement. *Handbook of partial least squares: Concepts, methods and applications*, 47-82.

177. Walker, H., Di Sisto, L., and McBain, D. (2008). Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors. *Journal of Purchasing and Supply Management*, *14*(1), 69-85.

178. Walmsley, T. G., Ong, B. H., Klemeš, J. J., Tan, R. R., and Varbanov, P. S. (2019). Circular Integration of processes, industries, and economies. *Renewable and Sustainable Energy Reviews*, *107*, 507-515.

179. Webster, J., and Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly*, xiii-xxiii.

180. Wolf, M., Kleindienst, M., Ramsauer, C., Zierler, C., and Winter, E. (2018). Current and future industrial challenges: demographic change and measures for elderly workers in industry 4.0. *Annals of the Faculty of Engineering Hunedoara*, *16*(1), 67-76.

181. Wortmann, F., and Flüchter, K. (2015). Internet of things. *Business and Information Systems Engineering*, *57*(3), 221-224.

182. Yadav, G., Luthra, S., Jakhar, S. K., Mangla, S. K., and Rai, D. P. (2020). A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case. *Journal of Cleaner Production*, *254*, 120112.

183. Yu, C., Xu, X., and Lu, Y. (2015). Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing–concepts and relationships. *Manufacturing Letters*, *6*, 5-9.

184. Zhong, R. Y., Xu, X., Klotz, E., and Newman, S. T. (2017). Intelligent manufacturing in the context of industry 4.0: a review. *Engineering*, *3*(5), 616-630.

185. Zhou, X., Song, M., and Cui, L. (2020). Driving force for China's economic development under Industry 4.0 and circular economy: Technological innovation or structural change?. *Journal of Cleaner Production*, *271*, 122680.

Appendix A

Questionnaire

This research work is being conducted as a survey of the Indian manufacturing industry for the purpose of statistical analysis on Industry 4.0 and circular economy. It is requested to spare some time and respond to the enclosed questionnaire. The objective of this study is purely research and academic-oriented, and all responses will be kept confidential.

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* Required

1. (i) Name of the Organization (optional)

____

2. (ii) Year of Establishment

____

3. (iii) Annual Turnover of the Organization (INR in Million).

- Less than 100
- In between 100-300
- In between 300-500
- Greater than 500

4. (iv) Number of employees in the organization.

- Less than 100
- In between 100-300
- In between 300-500
- Greater than 500

5. (V) Type of sector

- Manufacturing
- Automobile
- Aerospace

- Food and beverage
- Marketing and Service
- Other: ____________________

6. (vi) Products/Services offered by the organization

____

7. (vii) Industry 4.0 technologies implemented by the organization.

- [ ] Cyber-Physical-Systems
- [ ] Internet of Things
- [ ] Big Data
- [ ] Cloud Computing
- [ ] Cybersecurity
- [ ] Artificial Intelligence
- [ ] Additive Manufacturing
- [ ] Other

8. (viii) Circular Economy approaches implemented by the organization.

- [ ] Reduce
- [ ] Reuse
- [ ] Recycle
- [ ] Repairing
- [ ] Refurbished
- [ ] Remanufacturing
- [ ] Recover
- [ ] Reglass
- [ ] Refuse
- [ ] Other:

9. (ix) Circular supply chain activities outsourced by the organization.

- [ ] Product Acquisition
- [ ] Production Collection
- [ ] Transportation Inspection and Sorting Repairing
- [ ] Remanufacturing
- [ ] Recycling
- [ ] Disposal

☐ Other: ....

Factors affecting the implementation of Industry 4.0 and Circular Economy.

Please rate the following factors implemented by your organization based on the scale of 1 to 5 (1 for Very Low, 2 for Low, 3 for Medium, 4 for High, and 5 for Very High).

1.1 Drivers in the implementation of Industry 4.0 in Circular Economy perspectives

(i) Availability of information and resources.

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Real-time monitoring and control of manufacturing processes.

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Improve decision-making process.

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Improvement of product customization.

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Increase of processes visualization and control

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

1.2 Barriers in the implementation of Industry 4.0 in Circular Economy perspectives.

(i) High implementation and infrastructure cost

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(ii) Lack of effective planning and top management commitment

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iii) Lack of IT facilities and smart product manufacturing systems

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iv) Lack of process digitization and automation

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(v) Improvement of manufacturing process

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

1.3 Enablers in the implementation of Industry 4.0 in Circular Economy perspectives

(i) CPSs, IoT and cloud manufacturing

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Reliability and scalability

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Preventive and predictive maintenance

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Integration and interoperability

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Global standard and data sharing protocols

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

1.4 Redesigning strategies in the application of Industry 4.0 in Circular Economy perspectives.

(i) Designing out waste

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(ii) Waste reduction

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iii) Keep product and material in reuse

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iv) Regenerate or recycle the natural system

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(v) Reclassification of materials

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(vi) Renewable Energy

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

1.5 Key issues in the application of Industry 4.0 in Circular Economy perspectives.

(i) Data security and privacy concerns

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Legal and ethical issues

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Operational issues

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Demographic issues

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Government rules and regulation

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

1.6 Current challenges in the implementation of Industry 4.0 in Circular Economy perspectives.

(i) Technological development

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Complexity in collaboration

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Data security and management

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Product technology improvement

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(v) Big data and analytics

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(vi) Strategic development and decision making ability

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(vii) Employment disruption

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(viii) Collaborative model

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(ix) Eco-efficiency of technological processes

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(x) Management support

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(xi) Analysis and strategy

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

2. Value Engineering Implementation in the implementation of Industry 4.0 in Circular Economy perspectives.

(i) Reduce product development cost

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Reduce power consumption

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Reduce CO2 emissions

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Reduce water consumption

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Human resource

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

3. Performance estimation of Industry 4.0 and Circular Economy

Please provide the following information related to performance parameters of Industry 4.0 and circular economy for your organization.

3.1 Economic Performance

(i) Reduce infrastructure cost

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Financial support

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Reduction of operational costs

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iv) Return on investment

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(v) Reuse/recycle/reduce costs

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

3.2 Environmental Performance

(i) Zero waste practices

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(ii) Maximize the circularity of the resources

(Mark only one oval)

	1	2	3	4	5	
Very low	⬭	⬭	⬭	⬭	⬭	Very high

(iii) Reduce resource extraction

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Reduction energy consumption, power consumption and CO2 emission

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Lean and green product manufacturing practices

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

3.3 Social Performance

(i) Training and skill development programs for employees

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(ii) Cognitive capabilities of the workforce

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iii) Response to customer complaints

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(iv) Increase worker safety

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

(v) Customer satisfaction

(Mark only one oval)

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

4. Respondent Profile

Kindly fill the following information. Every information you provided will be kept private and not shared to any third parties. We appreciate your time and effort in filling out this survey.

(i) Name and signature of the respond

(ii) Designation:

(iii) Organization:

(iv) Total Industrial Experience

(v) Email Address:

Please provide your feedback on this questionnaire and the issues at face in the space provided below.

Appendix B

Table B.1 XYZ Industry survey questionnaire

Criteria	Alternatives					Rating				
	A1	A2	A3	A4	A5	LI	I	AI	MI	VI
C1: Technological development										
C2: Complexity in collaboration										
C3: Data security and privacy										
C4: Data management										
C5: Big data and analytics										
C6: Strategic development										
C7: Employment disruption										
C8: Collaborative model										
C9: Decision-making ability										
C10: Management support										
C11: Analysis and strategy										
C12: Human resource										
C13: Social										
C14: Economic										
C15: Environment										

List of Publications from the Thesis

(i) List of Papers Published in International Journals

1. Sahu, A., Agrawal, S., and Kumar, G., "Integrating Industry 4.0 and circular economy: a review", Journal of Enterprise Information Management, 35 (3), 885-917, 2022. https://doi.org/10.1108/JEIM-11-2020-0465 (Pub: Emerald and Impact factor 5.661)
2. Sahu, A., Agrawal, S., and Kumar, G., "Triple Bottom Line Performance of Manufacturing Industry: A Value Engineering Approach", Sustainable Energy Technologies and Assessments, Vol. 56, pp. 103029. https://doi.org/10.1016/j.seta.2023.103029 (Pub: Elsevier and Impact factor 7.632)
3. Sahu, A., Agrawal, S., and Kumar, G., "Challenges of Implementing Industry 4.0 in Achieving Sustainable Development Goals: A Case of Indian Manufacturing Organization", Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. Accepted (Pub: Taylor & Francis and Impact factor 2.902).
4. Agrawal, S., Sahu, A., and Kumar, G. (2022). A conceptual framework for the implementation of Industry 4.0 in legal informatics. Sustainable Computing: Informatics and Systems, 33, 100650, 2022. https://doi.org/10.1016/j.suscom.2021.100650 (Pub: Elsevier and Impact factor 4.923)

(i) List of Papers presented/published in conference proceedings

1. Sahu, A., Agrawal, S., and Kumar, G., "Implementation Challenges of Industry 4.0 and Circular Economy: A DEMATEL Approach" 2nd International Conference on Industrial and Manufacturing Systems held at Punjab Engineering College, Chandigarh during 11-13 November 2021. (Best Paper Awarded in CIMS2021

Conference)

2. Sahu, A., Agrawal, S., and Kumar, G., "Circularity decisions of Industry 4.0 and Circular Economy in Manufacturing Organization" International Conference on Technological, Social and Economic Innovation through Artificial Intelligence, Data Science and Cyber Security held at Institute of Management Studies, Ghaziabad during 15-16 April, 2022. (Best Paper Awarded in ICTSEADC 2022 Conference)

3. Sahu, A., Agrawal, S., and Kumar, G., "Circular Performance of Industry 4.0 and Circular Economy Using Best Worst Method" Recent Advances in Materials, Manufacturing and Thermal Engineering held at Delhi Technological University during 8-9 July, 2022.

Profile of the Researcher

Abhishek Sahu is currently a research scholar in Delhi Technological University in the Department of Mechanical Engineering. He earned his Bachelor of Engineering degree in Mechanical Engineering from RGPV University, Bhopal and Master of Engineering degree in Advance Production Systems from NITTTR, Bhopal. His research interests include Industry 4.0, Circular Economy, Supply Chain Management, and Assembly Line Balancing. He has published various research articles and patents in International Journals and Conferences, including Journal of Enterprise Information Management, Sustainable Energy Technologies and Assessments, Environmental Science and Pollution Research, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, Sustainable Computing: Informatics and Systems, and The TQM Journal.