Analysis of industry 4.0 and circular economy enablers: a step towards resilient sustainable operations management

Analysis of Industry 4.0 and Circular Economy enablers: A step towards Resilient Sustainable Operations Management

Abstract:

Originating in Germany, Industry 4.0 quickly became the new standard with industries adopting it worldwide. However, in the hurry to become digitalized for increasing production and efficiency, industries have failed at embracing the sustainability aspect of production. With the rise in concern for environmental safety and the re-introduction of circular economy, the authors have identified the integration of I4.0 and CE as a strong research point for overcoming the obstacles in achieving sustainable operations management (SOM). The research explains the criticality of the integration of I4.0 and CE and how it is the next step in becoming sustainable and resilient in today's turbulent environment. The study incorporates a four-step hybrid methodology with the identification and validation of enablers as the first phase using the PRISMA statement and PF-Delphi technique respectively. The second phase employs the PF-AHP technique for calculating the criteria weights which are subsequently used in the third phase by applying PF-CoCoSo to rank the enablers in priority order. Lastly, sensitivity analysis is performed to check the robustness of the results. The paper identified service and policy framework as the most critical criteria and product lifecycle management as the highest priority enabler for achieving SOM. The authors have also put forward seven recommendations for industries looking to implement I4.0 and CE for SOM by taking instances from previous case studies.

Keywords: Industry 4.0, Circular economy, Sustainable operations management, Enablers, PF-Delphi, PH-AHP, PF-CoCoSo, Sensitivity analysis

1. Introduction:

The term Industrial revolution can be dated back to the 1760s. Often associated with the development of steam engines, the first industrial revolution (I1.0) signified urbanization and market economies' growth led by the dynamic increase in productivity and the spirited pursuit of scientific and technical endeavors (Xu et al. 2018, Philbeck and Davis 2018). The boom of electrical power in the 1840s (Sindhwani et al., 2022a) and the subsequent use of internal combustion engines as transport came to the second industrial revolution (I2.0). Known as the technological revolution, it was a time of rapid industrialization and the beginning of mass production (Xu et al., 2018). The third industrial (I3.0) revolution (the 1960s) is seen as the digital advancement age, introducing silicon-based semiconductor chips, transistors, and computers that played a significant role in automating production processes. It brings us to the fourth industrial revolution (I4.0), originating in Germany in 2011, defined as a step into the digital age (Rajput and Singh 2019, Lee et al. 2018). With the emergence of new technologies like artificial intelligence (AI), internet of things (IoT), blockchains, and many more, I4.0 gives the manufacturing industries a higher level of organization and better control over the product's complete lifecycle.

Industry 4.0 developed on the automation introduced during the I3.0 by making the manufacturing process more imaginative and flexible and providing autonomous decision-making capabilities to the machines. The need for I4.0 revolves around improving standard machines and developing them into conscious and self-learning machines, increasing the general performance and converting production processes into smart manufacturing (Vaidya et al., 2018). Man-machine interaction, real-time data monitoring, data analytics, better product management, horizontal and vertical integration are some of the needs that led to I4.0. Industry 4.0 also looks to work on the machine-machine and man-machine interaction, ensuring that the social and technical aspects bond together for a thriving human society (Sony and Naik, 2020). When applied to manufacturing, the I4.0 technologies provide real-time monitoring and control of production processes. Essential factors like energy consumption, customer orders, suppliers' data, production status, and flow of materials can be optimized to develop products that the customers want (Jabbour et al., 2018). Digitalization plays an essential role for industries in achieving Industry 4.0. The degree of digitalization can even be deemed the measurement parameter to determine the industry readiness for the transformation to intelligent manufacturing (Caiado et al., 2021).

Operations management (OM) is one of the critical areas where the use of I4.0 technologies gives benefits like increased flexibility, cost reduction, better service, higher product customization, and many more (Dev et al., 2020). If applied correctly, I4.0 can create smart factories and supply chains that lead to better implementation of technical equipment and help in increasing productivity and efficiency of the manufacturing processes. As much as I4.0 has helped bring industries into this new digitalized era, it is now stuck. Traditional businesses have not yet welcomed the idea of digital transformation. A belief that this jump into the digital era may negatively impact environmental sustainability has arisen (Jabbour et al., 2018). The recent ongoing pandemic has disrupted each sector's operations management, and it showcased how the current practices are neither sustainable nor resilient in the face of such obstacles (Belhadi et al., 2021a). Thus, a need for a shift towards sustainable operations management (SOM) arises.

The rate at which the natural resources are being consumed due to the consumption behavior of humans and the shorter product and service lifecycles has led researchers to ponder on the development of industries while keeping the environmentally friendly practices intact (Patel et al., 2021). Whenever one talks about sustainable practices, a single term always jumps to mind, i.e., circular economy (CE). Introduced in the early 1990s and then being sidelined, only to return as the mainstream strategy for environment sustainability (Patel et al., 2021), CE acts as the better possible replacement to the current linear flow model followed by the economic system. The traditional economy follows a practical recycling policy and thus misses out on various product life cycle areas where utilization of resources is lacking. On the other hand, CE follows a circular and cyclical approach emphasizing repair, remanufacturing, and reuse of the product (Korhonen et al., 2018). So, it can be defined as a regenerative system, and this regenerative nature is achieved by making the system a closed loop where resource and energy wastage can be minimized by scrutinizing the entire lifecycle of the product (Geissdoerfer et al., 2017). The essence of CE relies on using reusable materials to produce products and services so that one person's waste can act as a resource for the other. This cannot be achieved without the adoption of reusable resources for production. Hence, one can derive that CE heavily depends on the industries to adopt such materials and resources in their manufacturing tendencies (Piscitelli et al., 2020).

I4.0 and CE are the two faces of a coin (Garcia-Muiña et al., 2018). As the name suggests, CE is circular and regenerative, so all the resources must be used for maximum efficiency and be treated such that the impact on the environment when they are reintroduced into it should be minimum. While I4.0, due to its prevalent hold on the organizations and their resources, can encourage a circular approach and the establishment of new business models to incorporate the environmental well-being aspect (Spaltini et al., 2021). I4.0 technologies allow us to transition to CE. Technologies like AI (artificial intelligence), BDA (big data analytics), IoT (internet of things), AM (additive manufacturing), and others help gather real-time information and allocate resources, giving better control over the product's lifecycle (Gupta et al., 2021). This higher level of control enables us to minimize wastage with CE. This I4.0-CE nexus will keep the material flowing, creating sustainable supply chains (Rajput and Singh, 2019), making operations management more effective. The integration of I4.0 and CE can be strategically applied to help industries in achieving operational excellence. Thus, it can be established that for moving towards a sustainable future with sustainable operations management, the integration of I4.0 and CE is essential.

The term sustainability has recently met with a lot of attention from a research point of view. Many studies have been conducted previously for the integration of I4.0 and CE as a means to achieve sustainability. Bag et al., 2021 has researched the relation between I4.0 technologies (BDA and AI) and sustainable manufacturing practices and CE, Gupta et al., 2021 focused on identifying the practices involved in I4.0, cleaner production (CP) and CE for assessing the sustainability performance of industries, Shayganmehr et al., 2021 works on identifying the enablers of I4.0 for achieving CP and CE. However, none of the studies are oriented towards the fusion of I4.0 and CE enablers for the attainment of SOM. This fusion of I4.0 and CE to attain SOM requires qualitative and quantitative analysis of the effect of this nexus on the system. Through this study, the authors contribute to helping provide recommendations for adopting and implementing a SOM. Along the lines of this in-depth analysis, the researchers pose the RQ (research question):

RQ-1: What are the criteria and enablers for I4.0 and CE to achieve SOM?

Identification of the enablers of any concept will allow for its proper implementation and lead to a better success rate in using the said concept to achieve the organizational aims and goals. Finding the criteria and enablers of I4.0 and CE will help in integrating them as well as showcasing their interdependency. Thus, the first step in our study was the identification of the criteria and enablers of I4.0 and CE. To answer the posed RQ, the authors had to deal with vague data and performed an in-depth analysis of the previous studies to identify the enablers and selected only the quality articles in this research and reported them systematically with the help of the PRISMA approach. A research questionnaire was also circulated to collect the expert's data to select enablers. Further, to confirm and validate the inclusion of these enablers, the Pythagorean fuzzy Delphi approach is used. However, a need for assessment and prioritization of these criteria and enablers arises. Thus arises our second RQ.

RQ-2: How can these criteria and enablers' relative and overall importance be judged, and priority levels be found for achieving resiliency in SOM?

Finding the criteria and enablers alone would not solve the issue at hand but rather just provide us with a vague map to reach our goals. In order to optimize our path to SOM, it is necessary to find the rankings and the priority levels for the enablers. For answering RQ-2, the authors propose a novel three-stage hybrid methodology. In the first stage, Pythagorean Fuzzy AHP is applied to find the weightage of the criteria. Next, the selected enablers are ranked using the Pythagorean Fuzzy CoCoSo method, and finally, sensitivity analysis is done to check for robustness of the outcome. This three-stage integrated hybrid approach will help the authors to provide the framework for implementing resilient SOM.

The above framework will provide the result that will suggest the most important criteria and showcase the priority of enablers to be adopted for achieving SOM with I4.0 and CE in the industry. In the order of their ranking, the suggested criteria and enablers will be the most helpful for moving towards our goal. Using the result as a structure, the authors will provide the readers with the industry's implications and recommendations to achieve sustainability and resiliency.

This study aims to formulate an essential model for highlighting areas of focus for industries to develop resiliency and sustainability while competing in today's competitive environment. It will also provide research scholars and industrialists with a baseline to develop their future work. The authors will conduct a phase-wise analysis using the proposed novel framework that consists of powerful and effective MCDM techniques, such as PF-AHP that will help to rank the criteria according to their weightage and PF-CoCoSo that will provide the ranking priority of the enablers, allowing the readers to select the technology or technique in which they would like to invest. The research framework follows a four-step hybrid methodology. First, PF-Delphi is used for the acceptance or rejection of proposed enablers. PF-AHP is applied for finding out the criteria weightage, which allows us to rank them, and the weightage found is utilized in PF-CoCoSo to rank the enablers and provide a priority list for attaining SOM. Finally, sensitivity analysis is performed for checking the robustness and validating the result. The paper will also provide organizations with a clear view of the significant evolving theories on sustainability and firms, mainly corporate social responsibility and stakeholder theory (Chang et al., 2017).

The research paper follows the following structure: Section 2 discusses the literature review with problem definition and research highlights. Section 3 provides the adopted methodology, the detailed analysis of the result, and the sensitivity analysis. In Section 4, the authors discuss the study results along with the implications and recommendations. Section 5 provides the reader with the conclusion and limitations of the study, along with recommendations for future work. The flow of the study has been showcased with a flowchart in figure 1.

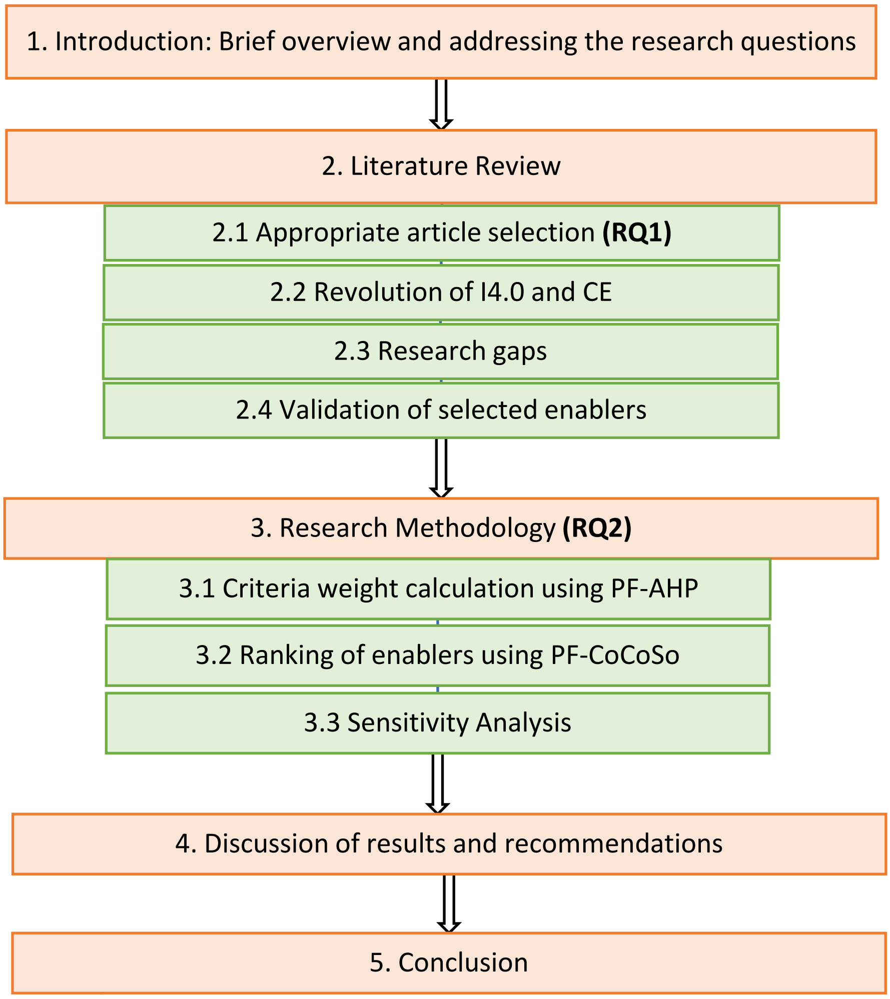

Fig. 1: Flow of Study

2. Literature Review

In this section, we will come across the required literature on industry 4.0 (I4.0), circular economy (CE), application of I4.0 and CE in achieving SOM, definitions of the listed criteria and enablers, research contributions of this study, and a list of possible issues that one might come across in moving towards a sustainable future.

2.1 Appropriate article selection:

This study followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for reporting the selected quality and relevant articles. The PRISMA group developed these guidelines in 2009 to help in deviating from the opiniated practices often adopted resulting in biased research by adopting a systematic and statistical approach of reporting for complete transparency (Selçuk, 2019).

Following the PRISMA guidelines will allow for the systematic reporting of the search undertaken for this research. The authors performed an in-depth search for research papers and articles on Scopus to assess the existing literature. Several keywords that aided in performing the search were “Industry 4.0”, “Circular Economy,” “Digitalized CE,” “Role of I4.0 and CE in SOM”, “Digital technologies circular economy,” “Collaborative robotics in Circular economy,” “I4.0 and CE enablers”. The search brought forth many articles, which were further sorted according to selection criteria such as year of publishing, language, document type etc., narrowing down the final eligible articles in the meta-analysis. The time selected for the scope of this search was 2016-2021. Only studies in English language and under the category of articles, conference papers and reviews were considered. In the first step, the non-relevant articles, which did not come under the scope of the study were removed. Next, based on the stated criteria the remaining studies were assessed and the ones not meeting the inclusion criteria and which were duplicate were also excluded. Further, the studies that did not state the enablers or criteria clearly were excluded and finally 34 research papers were considered significant to the current research. The complete finalization process is shown in Fig. 2. From the papers, the authors were able to finalize 5 criteria and 15 probable enablers for industry 4.0 and circular economy and taken their impacts on achieving sustainable operations management into consideration for further analysis. Tables 2 and 3 represent the selected criteria and enablers and the supporting literature.

The selection of enablers can be subjective since different people might have different opinions, leading to contradictory assessments. In order to keep the judgment unbiased and limit the ambiguous nature of research, authors have selected the Pythagorean Fuzzy Delphi approach (Sindhwani et al., 2022b, Ishikawa et al., 1993) for finalizing the enablers. Experts’ opinions are collected on the listed enablers in a questionnaire survey circulated amongst the panelists. The data collected is then quantitatively checked for selection/rejection of enablers using the PF-Delphi method. The steps to be followed and an in-detail analysis of the approach are discussed in section 2.4 (validation of selected enablers).

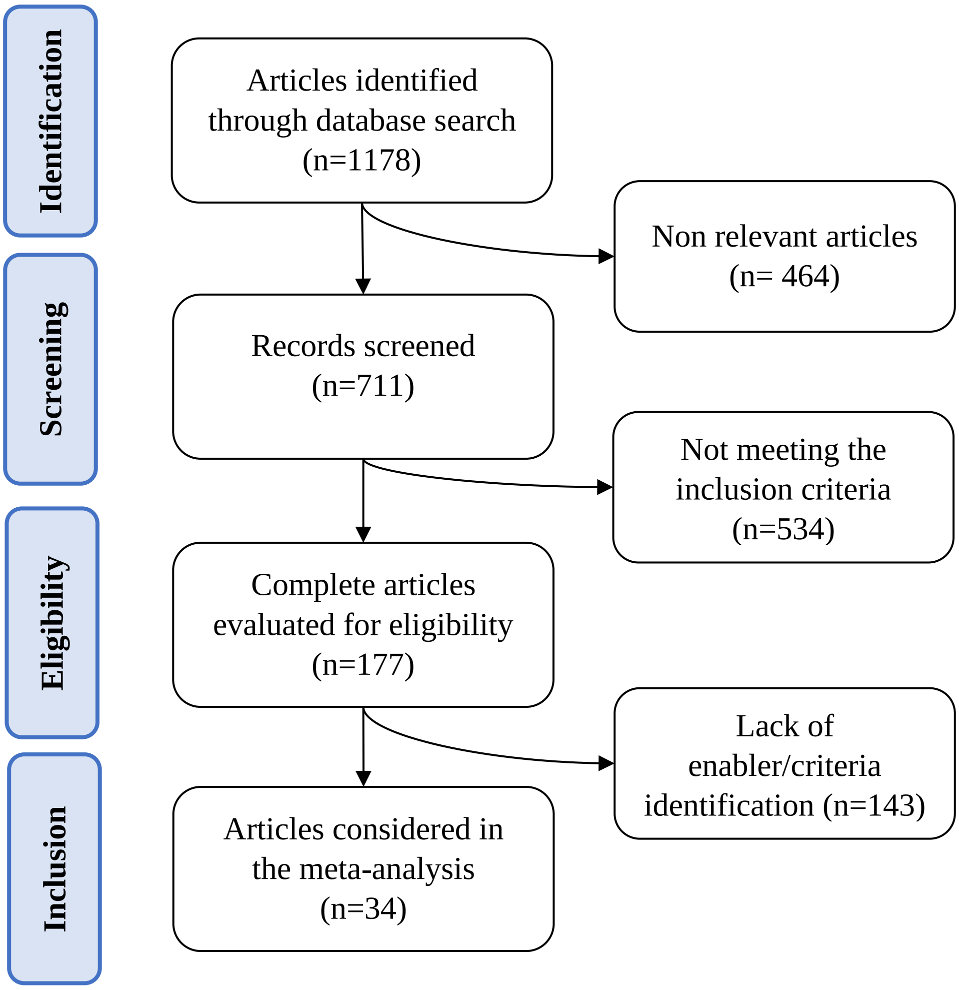

Fig. 2: Article selection by PRISMA

2.2 Revolution of I4.0 and CE

Industry 4.0 has brought forth the digital revolution in which industries have been suggested to change their methods to adopt digital technologies and embrace the idea of digitalization by making necessary changes to their business models, products, and services (Devi et al., 2020). Developed to achieve a higher degree of automation with accuracy and precision, I4.0 uses technologies like CPS, IoT, big data etc., to make the process more efficient and dynamic (Rajput and Singh, 2019). There is no clear indication and a lack of agreement about the classification of the technologies that act as the pillars of I4.0. Commonly accepted and identified technologies include CPPS, IoT, big data analytics, additive manufacturing, and simulation (Rosa et al., 2020). These technologies, when applied correctly, can prove to be immensely useful. Big data makes use of ubiquitous data and processes it accurately (Kumar et al., 2019), which can then be used for forecasting, sales, logistics etc., to improve the performance of the operations management field (Bag et al., 2021). IoT provides better process monitoring and helps create smart supply chains (Shayganmehr et al., 2021) using wireless modes of communication to improve the cooperative relationship of humans, devices, and machines (Rosa et al., 2020).

A circular economy was introduced to move away from the current practice of following a linear structure of scraping the materials after one-time use only, resulting in a massive and rapid depletion of the Earth's resources (Korhonen et al., 2018). CE can be considered a closed loop of an economic system that aims to help the product retain as much value as possible even after multiple uses (Geissdoerfer et al., 2017). CE looks to link economic development and environmental protection through activities like cleaner production and product lifecycle management to achieve sustainable production and consumption (Gupta et al., 2021). Proper implementation of CE can help us minimize wastage of our resources and make the production process cleaner and greener allowing us to achieve net-zero (Tet et al., 2021).

The current world scenario indicates that our production and consumption cycles are causing a massive rift in the maintained ecology. A move towards sustainable practices has become necessary for industries that want to survive in the current competitive environment. Sustainability as a concept has emerged to dampen the harmful and rapid depletion of our natural resources (Mardani et al., 2015). To achieve sustainable growth, the United Nations have proposed 17 sustainable development goals (SDGs) that all countries need to act upon and meet (Khoshnava et al., 2019). The integration of I4.0 and CE will help us achieve and meet the said goals. Hence, the I4.0-CE nexus has become necessary for every organization that wants to attain flexibility, resilience (Belhadi et al., 2022), and sustainability.

2.3 Research Gaps

Operations management is a field where scientific and systematic methods allow organizations to make near-optimal decisions. Forecasting, inventory management, risk analysis, supply chain management are some of the functions that come under operations management (Choi et al., 2018). However, the operations management discipline is neither sustainable nor resilient. The rapid consumption of natural resources and the effect of the COVID-19 pandemic on global supply chains are testaments to the former. The study of the I4.0-CE nexus will help us move towards data-driven sustainable operations management.

From the research, we will understand the relationship between I4.0 and CE, their enablers and common criteria, and their application in achieving a sustainable and resilient operations management sector. For understanding any new topic of research and realizing its importance, it is very necessary to determine the factors that affect it and further analyze them. In our research we have worked on identifying the enablers and criteria of I4.0 and CE for achieving SOM and later analyzing them. Enablers can be regarded as something that provides power to a particular feature to achieve its end effect. In this case, we are looking to find ways of successfully enabling and implementing I4.0 and CE to reach the end result of achieving SOM. The selected enablers are then also judged against five criteria that are important to the success of any organization in implementing I4.0 and CE. When ranking the enablers using PF-CoCoSo method, the criticality of the criteria (its weightage) and the relative importance of the enablers with respect to the criteria are assessed. The critical criteria assessed in this research directly impact the ability of industries to meet the above goal and help optimize the outcomes. A higher level of government support and better policies will undoubtedly help industries and employees adopt the new technologies and practices, which will increase efficiency while making the process more sustainable (Shayganmehr et al., 2021). Similarly, establishing a better-suited industrial ecosystem will improve the current machines and promote higher productivity (Devi et al., 2020). For a smoother transition, importance should also be given to the man-machine interactions, and special care needs to be taken to ensure that the quality of production is improved in the manufacturing processes. Minimizing the wastage is another essential criterion that must be appropriately addressed to optimize the resources (Cagno et al., 2021; Behl et al., 2018; Patil et al., 2021). Finally, infrastructure and equipment used for the processes should be updated to implement CE (Patel et al., 2021) successfully, ensure smooth flow, and provide automation. In this way, we can move towards resilient SOM.

These five criteria will help and enable any organization to overcome the current obstacles in achieving a competitive, sustainable and resilient future. However, every organization might not have the means and resources to adopt them. The study is reliant on the opinions of the experts and the authors have used purposive sampling strategy for selecting the experts. Table 1 provides the details of the experts who have provided their inputs in this study. A total of eight experts were chosen for this study having different areas of expertise and relevant experience in the industry. For conducting an unbiased study that relates and translates the findings for all the sectors, the authors purposively chose experts that are from different areas of industry and have different academic backgrounds.

Table 1: Details of Experts

Experts	**Working in Industry**	**Academic Background**	**Work Experience (years)**	**Areas of Expertise**
E1	Automobile	M-tech	12	Purchase
E2	Manufacturing	MBA, M-Tech	15	Maintenance
E3	FMCG	PHD	8	Sales
E4	Automobile	M-tech	11	Analyst
E5	Automobile	MBA	10	Data Science
E6	Supply Chain	B-Tech; BSc	13	Project manager
E7	Manufacturing	BCA, MBA	9	Analyst
E8	Manufacturing	M-Tech, MS	6	Digital Transformation

Table 2: Criteria for assessing I4.0 and CE enablers.

S. No.	***Criteria***	***Description***	***References***
C1	Service and Policy Framework	Service and Policy Framework looks to improve on the current level of production by taking help of laws and educating employees in various technologies for enabling I4.0 and CE.	Rajput and Singh, 2019 Shayganmehr et al., 2021
C2	Industrial Ecosystem	Industrial Ecosystem consists of leading industry technologies that help automate processes and achieve higher productivity.	Rajput and Singh, 2019 Devi et al., 2020 Shayganmehr et al., 2021
C3	Man-Machine Interaction	The link between humans and machines helps them develop and communicate better with each other and the physical world.	Shayganmehr et al., 2021 Devi et al., 2020
C4	Wastage Prevention	Waste Prevention will lead to proper utilization of resources to their full extent, thus reducing costs and improving company image.	Cagno et al., 2021 Atif et al., 2021
C5	Smart Infrastructure and Equipment	Smart Infrastructure and Equipment will improve production efficiency, ensure smooth flow, and provide automation.	Devi et al., 2020 Patel et al., 2021

Table 3: Enablers of I4.0 and CE

S. No.	***Enablers***	***Description***	***References***
A1	Laws, Policy, and Government Support	Supporting policies are directly involved in enabling I4.0 and CE. Good and favorable policies can lead to better quality, eco-friendly and ethical production. It can further help in achieving sustainable development.	Rajput and Singh, 2019; Shayganmehr et al., 2020; Patel et al., 2021; Rizos et al., 2016
A2	Waste Reduction	It deals with the 3 R's, Reduce, Recycle and Recover. It aims to minimize the amount of wastage produced and reuse the product to get maximum value.	Rajput and Singh, 2019; Atif et al., 2021; Gupta et al., 2021 Rosa et al., 2020
A3	Smart SCM and Factories	When combined with smart factories, smart supply chain practices will lead to better implementation of technical equipment and help increase the productivity and efficiency of the manufacturing processes.	Shayganmehr et al., 2020; Devi et al., 2020; Patel et al., 2021 Rizos et al., 2016; Vaidya et al., 2018 Gupta et al., 2021; Rosa et al., 2020

A4	Product Lifecycle Management	Getting a better handle on the entire lifecycle of the product will enable us to make better decisions in the production and consumption stage and drive us towards sustainability.	Devi et al., 2020; Atif et al., 2021 Cagno et al., 2021; Rosa et al., 2020
A5	Internet of Things (IoT)	IoT helps monitor the processes better and maintain the seamless connection between the equipment and services to improve data collection and efficiency.	Rajput and Singh, 2019; Shayganmehr et al., 2020; Devi et al., 2020; Spaltini et al., 2021; Cagno et al., 2021; Dutta et al., 2021 Jabbour et al., 2018; Vaidya et al., 2018 Gupta et al., 2021 Rosa et al., 2020
A6	Big Data	The higher quantity of collected data will help us make better and wiser decisions, providing new solutions to improve productivity.	Rajput and Singh, 2019 Shayganmehr et al., 2020 Devi et al., 2020 Spaltini et al., 2021 Cagno et al., 2021 Gupta et al., 2021; Nagar et al., 2021 Kumar et al., 2021 Bag et al., 2021; Dutta et al., 2022 Rosa et al., 2020
A7	Employee Training	Training employees in different aspects of I4.0 and CE will increase the Personal Staff Value(PSV) and make them more equipped and comfortable working with new technologies in a digital era.	Shayganmehr et al., 2020 Devi et al., 2020 Patel et al., 2021 Rizos et al., 2016 Bag et al., 2021
A8	Operational Efficiency	I4.0 and CE combined to offer new ways of dealing with problems and improving efficiency.	Shayganmehr et al., 2020 Devi et al., 2020 Patel et al., 2021
A9	Additive Manufacturing	Additive manufacturing can replace conventional manufacturing methods and offers more customization options with less wastage.	Shayganmehr et al., 2020 Devi et al., 2020 Spaltini et al., 2021 Cagno et al., 2021 Jabbour et al., 2018

			Gupta et al., 2021 Rosa et al., 2020
A10	BlockChain	It is regarded as an essential tool that helps maintain and regulate the financial flow.	Singh et al., 2022 Rajput and Singh, 2019 Shayganmehr et al., 2020 Cagno et al., 2021
A11	Management Participation	Participation of management-level employees in employing I4.0 and CE techniques and helping others by providing guidance will lead to better integration of the systems.	Shayganmehr et al., 2020 Devi et al., 2020 Patel et al., 2021 Rizos et al., 2016 Bag et al., 2021
A12	CPPS (Cyber-Physical Production Systems)	It has several coordinating systems connected and helps with the intercommunication between humans, machines, and the product.	Rajput and Singh, 2019 Devi et al., 2020 Jabbour et al., 2018 Bag et al., 2021 Rosa et al., 2020
A13	Horizontal and Vertical Integration	Horizontal and vertical integration ensures a smooth flow of material and information amongst various departments of the manufacturing plant.	Devi et al., 2020 Cagno et al., 2021
A14	Cloud Manufacturing	It is responsible for sharing and using the various distributed manufacturing resources in a centralized way that ensures a high usage level.	Rajput and Singh, 2019 Shayganmehr et al., 2020 Spaltini et al., 2021 Cagno et al., 2021 Jabbour et al., 2018 Vaidya et al., 2018
A15	Collaborative Robotics	Collaborative robotics develops a physical interaction between machines and humans to provide a better production quality in manufacturing processes.	Rajput and Singh, 2019 Shayganmehr et al., 2020 Mozos et al., 2020

2.4 Validation of selected enablers

The Delphi method, a powerful risk analytic tool (Turoff and Linestone, 1979), also assists in selecting or rejecting enablers from a set of given data. The Fuzzy Delphi method is a technique (Ishikawa et al., 1993) proposed that combines the fuzzy sets and the Delphi method to provide results concerning human reasoning (Zadeh et al., 1996). The PF-Delphi method was adopted to further expand the domain under consideration that uses the Pythagorean fuzzy sets (Miguel et al., 2019).

The following steps are followed for the PF-Delphi method:

- Step 1: Based on the decided criteria, the enablers are identified and listed for evaluation by experts as per their opinion in a survey form.
- Step 2: The form is distributed to the experts for evaluation. The data is obtained in linguistic terms and then changed into Pythagorean fuzzy numbers (PFNs) with the help of the scale shown in Table 4.

Table 4. Linguistic terms with PFN (Liu et al., 2021)

Linguistic Term	Abbreviation	PFN
Perfectly High	PH	(0.950, 0.200)
Very High	VH	(0.850, 0.350)
High	H	(0.700, 0.400)
Medium High	MH	(0.650, 0.450)
Average	A	(0.500, 0.550)
Medium Low	ML	(0.400, 0.650)
Low	L	(0.350, 0.750)
Very Low	VL	(0.250, 0.850)
Very Very Low	VVL	(0.200, 0.950)

Suppose ‘p’ enablers are selected and listed for evaluation from the ‘q’ number of experts.

Let $\tilde{O}_{ij}$ be the score evaluated for i^{th} enabler out of p enablers according to the j^{th} expert out of q in PFN (Kumar et al., 2019) as shown in equation (1).

$$\tilde{O}_{ij} = (m_{ij}, n_{ij}) \quad (1)$$

where, i = 1,2,3, … …, p; j = 1,2,3, … …, q.

- Step 3: Union operation is done on values from every row (Abdullah and Goh, 2019)

$$U_i = (\max_i m_{ij}, \min_i n_{ij}) = (m'_i, n'_i) \quad (2)$$

- Step 4: Calculation of hesitancy value using equation (3)

$$\pi'_i = 1 - m'^2_i - n'^2_i \quad (3)$$

- Step 5: Defuzzification is then done to obtain the crisp values for each enabler (Karasan et al., 2019) using equation (4)

$$d_f(U_i) = \frac{1 + m'^2_i - n'^2_i - \pi'^2_i}{2} \quad (4)$$

Pythagorean Fuzzy Delphi was used to account for the uncertainty in identified 15 enablers. A questionnaire was created to help collect the opinions of industry experts in a linguistic form which were later converted into PFNs using the conversion scale. A threshold value of 0.6 was finalized to accept or reject any enabler (Shen et al., 2019, Sindhwani et al., 2022a). Thoughts and suggestions of the experts were also entertained to make sure that everyone was pleased with the choices made for the criteria and enablers. The data collected was then analyzed, and all the enablers cleared the threshold value and hence, were accepted. Table 5 shows the analysis of the PF-Delphi method. The final enablers are showcased in Figure 3. The hesitancy function represents the hesitant nature or lack of commitment associated with the membership grade (Yager and Abbasov, 2013). In the next section, the authors have discussed the methodology adopted to rank the criteria and enablers to provide the industrialists with a priority order for the successful implementation of I4.0 and CE.

Table 5: Selection/Rejection of enablers based on their defuzzified values

Enablers	PF-Weights		Hesitancy	Defuzzified value	Selected/ Rejected
	m	n	π		
A1	0.95	0.2	0.0575	0.9296	S
A2	0.95	0.2	0.0575	0.9296	S
A3	0.95	0.2	0.0575	0.9296	S
A4	0.95	0.2	0.0575	0.9296	S
A5	0.95	0.2	0.0575	0.9296	S
A6	0.95	0.2	0.0575	0.9296	S
A7	0.95	0.2	0.0575	0.9296	S
A8	0.95	0.2	0.0575	0.9296	S
A9	0.95	0.2	0.0575	0.9296	S
A10	0.95	0.2	0.0575	0.9296	S
A11	0.95	0.2	0.0575	0.9296	S
A12	0.95	0.2	0.0575	0.9296	S
A13	0.95	0.2	0.0575	0.9296	S
A14	0.95	0.2	0.0575	0.9296	S
A15	0.85	0.35	0.155	0.7880	S

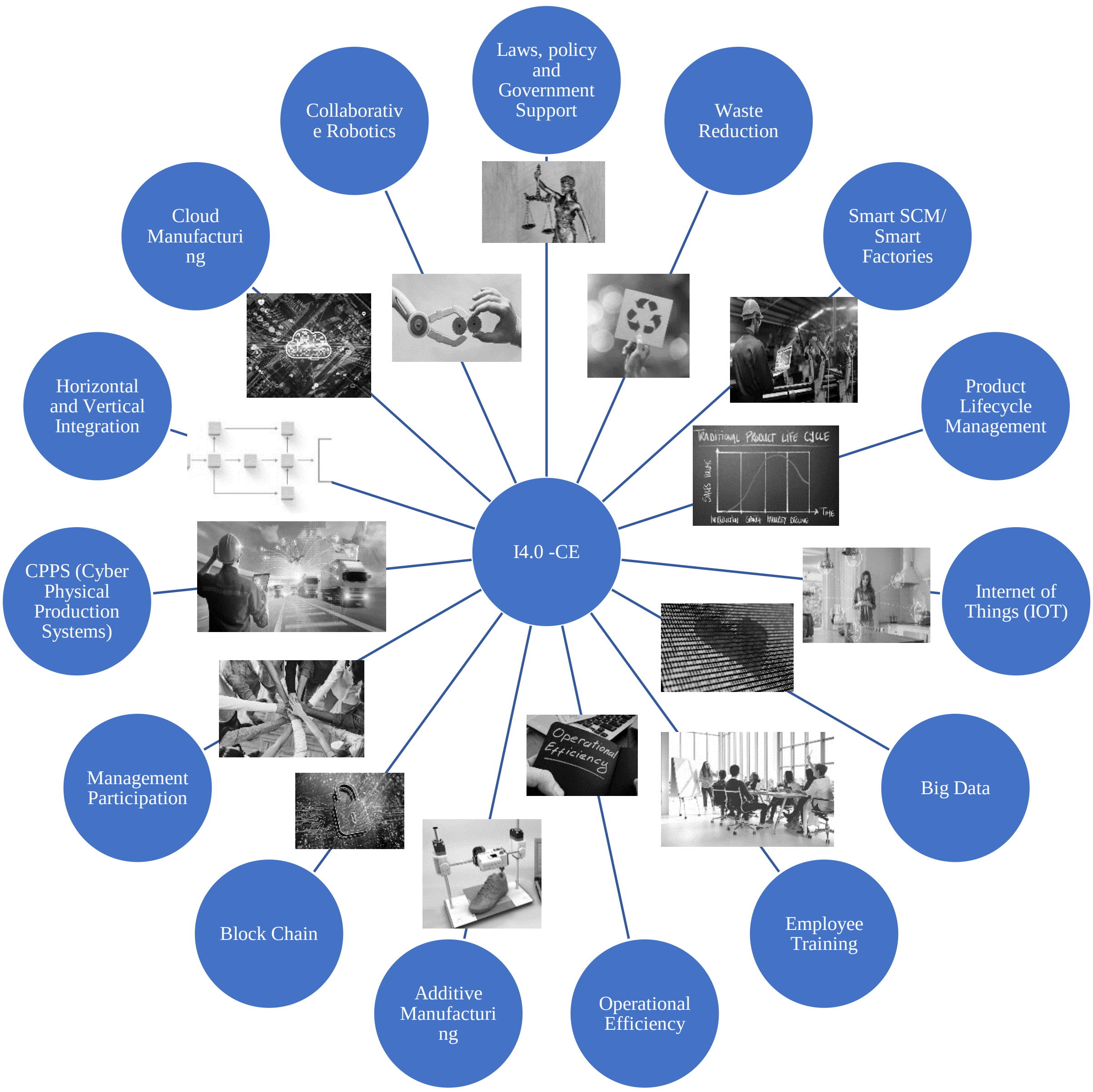

Fig. 3: Enablers of Industry 4.0 and Circular Economy

3. Methodology

This section will see the methodology adopted to find the weightage of the criteria and subsequently rank the enablers using he criteria weights. It involves three steps. Firstly, the criteria weights are calculated using the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) method. The enablers' ranks were then calculated in the next step by the Pythagorean Fuzzy Combined Compromise Solution (PF-CoCoSo) method. In the last step, sensitivity analysis is performed to check the robustness of the results.

3.1 PF-AHP

AHP is regarded widely as a productive tool for multi-criteria decision-making (MCDM) problems (Gandhi et al., 2016; Sindhwani et al., 2022a). Weighed to other methods such as ANP, ELECTRE, and TOPSIS, AHP produces better results (Ghorabaee et al., 2017). PF-AHP combines classical AHP with PFNs used to assign relative importance values. It is preferred to AHP due to its simplicity and the ability to account for any vagueness or inaccuracies in the data (Ilbahar et al., 2018).

The following steps are followed for PF-AHP: (Lahane and Kant, 2021, Ilbahar et al., 2018, Sindhwani et al., 2022b)

- Step 1: The experts' opinions are converted from linguistic terms to PFNs using Table 6, and simultaneously a pair-wise comparison matrix $R = (r_{ik})_{p\times p}$ is created for all criteria.

Table 6 for the scale of relative importance for AHP (Ilbahar et al., 2018)

Linguistic term	Abbreviation	PFN as IVPFN			
		m_L	m_U	n_L	n_U
Certainly Low Importance	CLI	0	0	0.9	1
Very Low Importance	VLI	0.1	0.2	0.8	0.9
Low Importance	LI	0.2	0.35	0.65	0.8
Below Average Importance	BAI	0.35	0.45	0.55	0.65
Average Importance	AI	0.45	0.55	0.45	0.55
Above Average Importance	AAI	0.55	0.65	0.35	0.45
High Importance	HI	0.65	0.8	0.2	0.35
Very High Importance	VHI	0.8	0.9	0.1	0.2
Certainly High Importance	CHI	0.9	1	0	0
Exactly Equal	EE	0.1965	0.1965	0.1965	0.1965

- Step 2: Using the following equations (5) and (6), a difference matrix, $D = (d_{ik})_{p\times p}$ is formed.

$$d_{ik_L} = m_{ik_L}^2 - n_{ik_U}^2 \quad (5)$$

$$d_{ik_U} = m_{ik_U}^2 - n_{ik_L}^2 \quad (6)$$

- Step 3: Use the equations (7) and (8) to form the multiplicative interval matrix, $S = (s_{ik})_{p\times p}$

$$s_{ik_L} = \sqrt{1000^{d_L}} \quad (7)$$

$$s_{ik_U} = \sqrt{1000^{d_U}} \quad (8)$$

- Step 4: For each entry of the matrix R (from step 2), calculate the determinacy value, $\tau = (\tau_{ik})_{p\times p}$ using equation (9)

$$\tau = 1 - (m_{ik_U}^2 - m_{ik_L}^2) - (n_{ik_U}^2 - n_{ik_L}^2) \quad (9)$$

- Step 5: Before normalization, use equation (10) to form the matrix of weights, $T = (t_{ik})_{p\times p}$

$$t_{ik} = \frac{(s_{ik_L} + s_{ik_U})}{2} \tau_{ik} \quad (10)$$

- Step 6: The final criteria weights are calculated using equation (11)

$$W_i = \frac{\sum_{k=1}^{p} t_{ik}}{\sum_{i=1}^{p}\sum_{k=1}^{p} t_{ik}} \quad (11)$$

For calculation of the criteria weights, a survey was made and circulated among the experts to document the relative importance of each criterion concerning others for their pair-wise comparison. The data obtained was converted from linguistic terms to IVPFNs (Karasan et al., 2019) using the conversion scale from Table 6 and then processed through the above steps to get the final criteria weights. The interval multiplicative matrix values and final criteria weights are shown in Tables 7 and 8, respectively.

Table 7: Interval multiplicative matrix values table

EF	EF-1				EF-2				EF-3				EF-4				EF-5			
	m(L)	m(U)	n(L)	n(U)	m(L)	m(U)	n(L)	n(U)	m(L)	m(U)	n(L)	n(U)	m(L)	m(U)	n(L)	n(U)	m(L)	m(U)	n(L)	n(U)
EF-1	0.1965	0.1965	0.1965	0.1965	0.9	1	0	0	0.9	1	0	0	0.35	0.45	0.55	0.65	0.8	0.9	0.1	0.2
EF-2	0	0	0.9	1	0.1965	0.1965	0.1965	0.1965	0.8	0.9	0.1	0.2	0.65	0.8	0.2	0.35	0.55	0.65	0.35	0.45
EF-3	0	0	0.9	1	0.1	0.2	0.8	0.9	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.65	0.8	0.2	0.35
EF-4	0.55	0.65	0.35	0.45	0.2	0.35	0.65	0.8	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55
EF-5	0.1	0.2	0.8	0.9	0.35	0.45	0.55	0.65	0.2	0.35	0.65	0.8	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965

Table 8: Calculated criteria weights

EF	W
EF-1	0.6303
EF-2	0.2025
EF-3	0.0831
EF-4	0.0523
EF-5	0.0318

3.2 PF-CoCoSo

CoCoSo (Combined Compromise Solution) is a new and effective method (Yazdani et al., 2019, Yazdani et al., 2019, Peng et al., 2020; Sindhwani et al., 2022c) that provides us with a consistent solution by using EWP (Exponentially Weighted Product) and SAW (Simple Additive Weighting) models with aggregation strategies (Lahane and Kant, 2021). Combining CoCoSo with PFNs helps us in reducing the ambiguities often involved in decision-making (Sindhwani et al., 2022a). PF-CoCoSo is being used here to find the ranking of the enablers. In this method, the experts' inputs are recorded for every enabler's relative importance to the five criteria. The weightage of the criteria weights calculated previously in PF-AHP is factored in to finalize the rankings of the enablers. The final ranking are thus also representative of the weightage of the criteria and is heavily influenced by them.

The following steps are followed for PF-CoCoSo:

- Step 1: Using the experts' opinion in linguistic terms to create a decision matrix, $D = (d_{ij})_{p\times q}$
- Step 2: Using the scale on Table (4) to convert the linguistic terms into PFNs
- Step 3: Use the given equation (12) to generate a matrix of score function, $R = (r_{ij})_{p\times q}$
  $$r_{ij} = m_{ij}^2 - n_{ij}^2 - \ln(1 + \pi_{ij}^2) \quad (12)$$
- Step 4: Use the equations (13) and (14) to convert the previous matrix into an orthonormal Pythagorean Fuzzy matrix, $R' = \left(r'_{ij}\right)_{p\times q}$
  $$r'_{ij} = \frac{r_{ij} - \min_i r_{ij}}{\max_i r_{ij} - \min_i r_{ij}} \text{; for benefit criterion} \quad (13)$$
  $$r'_{ij} = \frac{\max_i r_{ij} - r_{ij}}{\max_i r_{ij} - \min_i r_{ij}} \text{; for cost criterion} \quad (14)$$
- Step 5: The weighted comparability sequence total is calculated using equation (15)
  $$S_i = \sum_{j=1}^{q}(W_j \times r'_{ij}) \quad (15)$$
- Step 6: The power-weight comparability sequence total is calculated using equation (16)

$$P_i = \sum_{j=1}^{q}(r'_{ij})^{W_j} \quad (16)$$

- Step 7: Equations (17), (18), and (19) are used to calculate the relative score with aggregation strategies

$$K_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{p}(P_i + S_i)} \quad (17)$$

$$K_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \quad (18)$$

$$K_{ic} = \frac{\lambda S_i + (1-\lambda)P_i}{\lambda \max_i S_i + (1-\lambda)\max_i P_i} \quad (19)$$

- Step 8: Use equation (20) to calculate the final assessment value K_i and then rank the alternatives in decreasing order of K_i
  $$K_i = \sqrt[3]{K_{ia}K_{ib}K_{ic}} + \frac{K_{ia} + K_{ib} + K_{ic}}{3} \quad (20)$$
  In this way, the alternatives are ranked.

K_{ia} represents the Arithmetic Mean of Weighted Sum Model (WSM) and Weight Product Model (WPM), K_{ib} represents the sum of relative scores of WSM and WPM, compared to best, and K_{ic} represents a balanced compromise of WSM and WPM scores. λ is a deterministic parameter chosen by the DM (Yazdani et al., 2019).

Employed to rank the enablers according to their relative importance for selected criteria, PF-CoCoSo makes use of the criteria weights obtained using PF-AHP to calculate the WSM and WPM scores and also uses aggregation strategies to find a balance between them. The data for these calculations were obtained using a questionnaire circulated among experts to gather their linguistic opinions and subsequently changed to PFNs with the help of the scale shown in Table 4. For finding the orthonormal Pythagorean fuzzy matrix, the criteria were distinguished from each other as benefit criteria (C1) and cost criteria (C2, C3, C4, C5). The ranks of the enablers calculated from k_i values is shown in Table 9.

Table 9: Final ranks of enablers

	k_{ia}	k_{ib}	k_{ic}	k_i	Rank
A1	0.06841	4.882366	0.794154	2.557495	9
A2	0.057974	5.317133	0.672998	2.608015	7
A3	0.050491	2.101158	0.586136	1.308773	15
A4	0.084866	5.886164	0.98518	3.108251	1
A5	0.071799	6.076333	0.833495	3.040973	2
A6	0.071724	6.060785	0.832624	3.034369	3
A7	0.078265	4.904409	0.908558	2.667631	5
A8	0.067337	4.741142	0.781694	2.492981	10
A9	0.069266	3.737991	0.804089	2.129796	13
A10	0.070827	5.105117	0.822214	2.666803	6
A11	0.064008	3.947058	0.743051	2.157294	12
A12	0.068626	4.919102	0.796663	2.573612	8
A13	0.073468	5.924277	0.852866	3.00222	4
A14	0.054511	4.659757	0.632802	2.326073	11
A15	0.048427	2.954579	0.562172	1.620061	14

The highest value of k_i was obtained by product lifecycle management (A4) and received rank 1. Following it closely, we can see IoT (A5), big data (A6), horizontal and vertical integration (A13), and employee training (A7) coming in at positions 2,3,4,5, respectively. The rest of the enablers were also ranked similarly in the decreasing order of the k_i values.

3.3 Sensitivity Analysis

Sensitivity analysis is a necessary and efficient tool for checking the robustness of the framework results (Mangla et al., 2015). The authors have varied the experts' input to check for the robustness of the research.

The criteria C1 and C2, namely service and policy framework and industrial ecosystem, were recorded as the highest criteria weights, coming in at first and second positions, respectively. Thus, any change in their weights would impact the other criteria significantly. The criteria weights were varied on a scale ranging from 0.9 to 0.1 times the weight of each criterion. On applying this technique on C1 as shown in Table 10, a significant amount of change was observed in the weights of the other criteria. The new obtained criteria weights when used for ranking the enablers resulted in various different results for prioritization as shown in Table 11.

Similarly, the criteria weight for C2 was varied in the same range and the changes observed are shown in Table 12, and the changes in rankings recorded are shown in Table 13. The variations have also been showcased graphically in Figure 4 and Figure 5, respectively. On comparing Figures 4 and 5, we can see the difference in several variations. The different colors shown in the figures 4 and 5 represent the different series that reflect the ranking of the enablers. Series 1 represents the normal distribution, series 2 represents the distribution when the criteria weights are varied by a factor of 0.9. Similarly, series 3 represents the distribution when the criteria weights are varied by a factor of 0.8 and so on. When the weight for criteria C1 is varied, the graph gets scattered throughout, laying out the changes in the ranking of enablers. On doing the same for criteria C2 (Figure 5), variations observed are nominal compared to the former. This showcases the importance of service and policy framework in achieving implementation of I4.0 and CE for SOM and validates it as the highest weighted criteria. Hence, the results have been successfully checked for robustness.

Table 10: Changing weightage of criteria when running sensitivity analysis on criteria 1

Criteria	**Actual**	**.9**	**.8**	**.7**	**.6**	**.5**	**.4**	**.3**	**.2**	**.1**
C1	.630301	.5673	.5042	.4412	.3782	.3152	.2521	.1891	.1261	.0630
C2	.202491	.2370	.2715	.3061	.3406	.3751	.4096	.4442	.4787	.5132
C3	.083104	.0973	.1114	.1256	.1398	.1539	.1681	.1823	.1965	.2106
C4	.052274	.0612	.0701	.0790	.0879	.0968	.1057	.1147	.1236	.1325
C5	.03183	.0373	.0427	.0481	.0535	.0590	.0644	.0698	.0752	.0807

Table 11: Changes in enabler's ranks when running sensitivity analysis on criteria 1

A	**Actual**	**.9**	**.8**	**.7**	**.6**	**.5**	**.4**	**.3**	**.2**	**.1**
A1	9	7	8	8	9	9	10	10	10	10
A2	7	10	10	11	12	12	11	11	11	11
A3	15	15	15	15	15	14	14	14	14	12
A4	1	2	1	1	2	2	2	3	3	5
A5	2	3	3	4	4	3	3	4	4	3
A6	3	4	4	5	5	4	5	5	5	4
A7	5	8	5	2	1	1	1	1	1	1
A8	10	9	9	10	11	11	12	12	12	13
A9	13	13	13	9	7	6	4	2	2	2
A10	6	5	6	6	6	7	7	8	9	9
A11	12	12	12	12	10	10	9	7	7	6
A12	8	6	7	7	8	8	8	9	8	8
A13	4	1	2	3	3	5	6	6	6	7
A14	11	11	11	13	13	13	13	13	13	14
A15	14	14	14	14	14	15	15	15	15	15

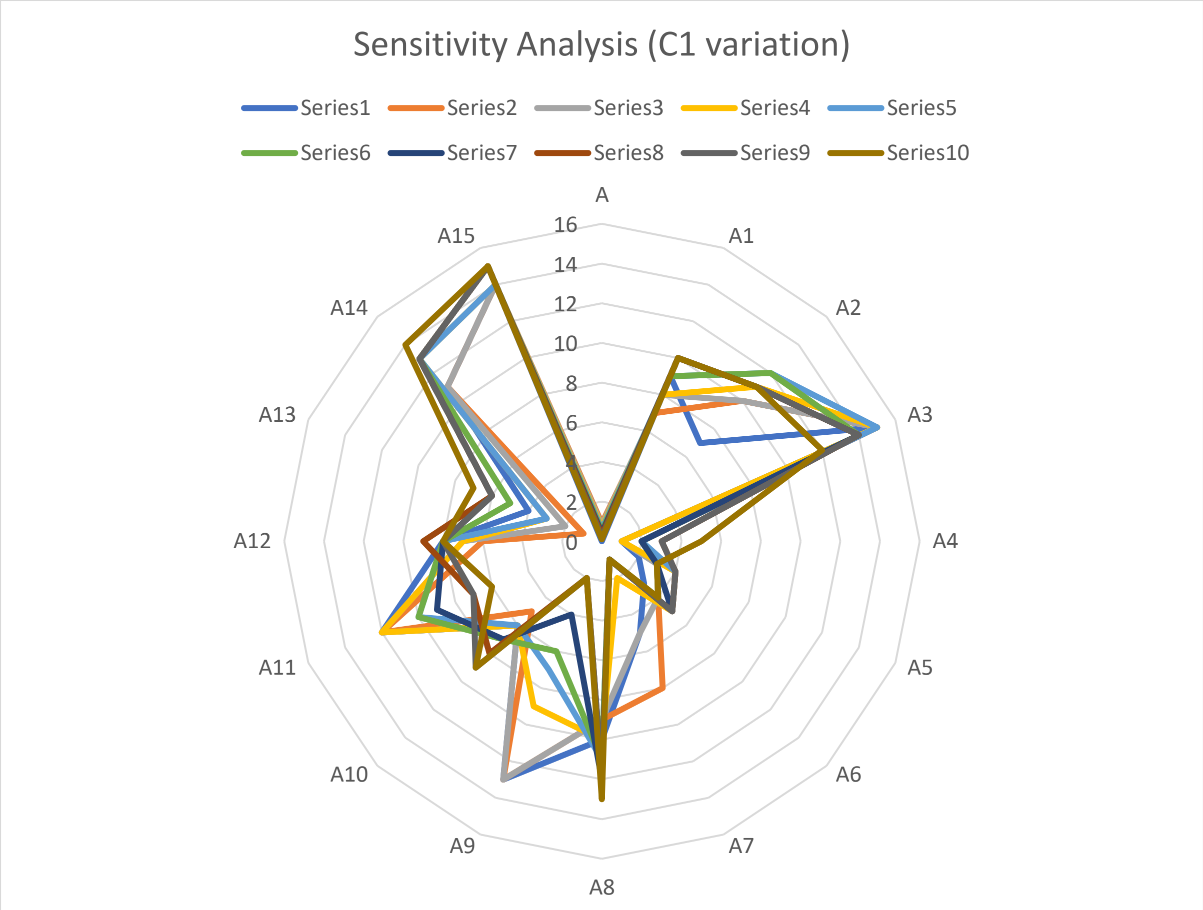

Fig. 4: Sensitivity analysis chart showing variations for C1

Table 12: Changing weightage of criteria when running sensitivity analysis on criteria 2

Criteria	**Actual**	**.9**	**.8**	**.7**	**.6**	**.5**	**.4**	**.3**	**.2**	**.1**
C1	.630301	.6463	.6623	.6783	.6943	.7103	.7263	.7423	.7583	.7743
C2	.202491	.1822	.1620	.1417	.1215	.1012	.0810	.0607	.0405	.0202
C3	.083104	.0852	.0873	.0894	.0915	.0937	.0958	.0979	.1000	.1021
C4	.052274	.0536	.0549	.0563	.0576	.0589	.0602	.0616	.0629	.0642
C5	.03183	.0326	.0334	.0343	.0351	.0359	.0367	.0375	.0383	.0391

Table 13: Changes in enabler's ranks when running sensitivity analysis on criteria 2

A	**Actual**	**.9**	**.8**	**.7**	**.6**	**.5**	**.4**	**.3**	**.2**	**.1**
A1	9	7	7	7	7	7	7	7	7	7
A2	7	9	9	9	9	9	9	9	8	8
A3	15	15	15	15	15	15	15	15	15	15
A4	1	2	2	2	2	2	2	2	2	2
A5	2	3	3	3	3	3	3	3	3	3
A6	3	4	4	4	4	4	4	4	4	4
A7	5	11	11	11	11	11	11	12	12	13
A8	10	8	8	8	8	8	8	8	9	9
A9	13	13	13	14	14	14	14	14	14	14
A10	6	5	5	5	5	5	5	5	5	5
A11	12	12	12	12	12	12	12	11	11	11
A12	8	6	6	6	6	6	6	6	6	6
A13	4	1	1	1	1	1	1	1	1	1
A14	11	10	10	10	10	10	10	10	10	10
A15	14	14	14	13	13	13	13	13	13	12

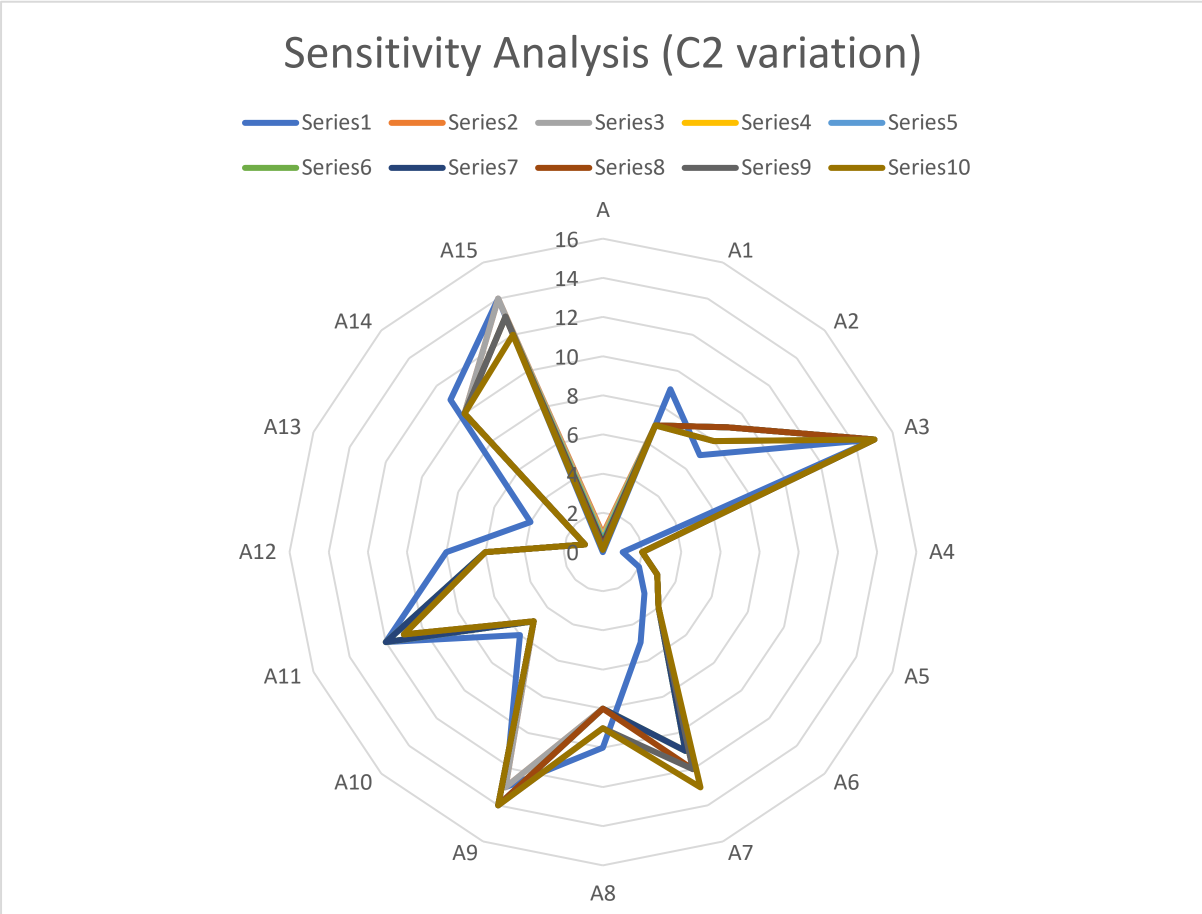

Fig. 5: Sensitivity analysis chart showing variations for C2

4. Discussion of results with implications and recommendations:

The study shows that the service and policy framework has the highest weightage of all criteria for implementing I4.0 and CE to achieve sustainable operations management. The criterion scored a weightage of 0.6303 in PF-AHP. The same can be seen in the literature review, where service and policy frameworks were regarded as key criteria for implementing I4.0 (Rajput and Singh, 2019). Company policies that make employees aware of I4.0 technologies and guide them for their proper implementation are critical to the success of any organization (Shayganmehr et al., 2021). Legislations supportive of providing end-users with eco-friendly quality products help in enabling the circular economy to reduce industrial emissions and maximize resource efficiency (Rajput and Singh, 2019).

Moreover, moving towards CE brings high upfront costs for the organizations. Supportive government policies can help industries cope on the economic front and adopt a cleaner and greener approach (Govindan and Hasanagic, 2018; Lang et al., 2022). Special consideration should be given to the service and policy framework from a managerial point of view as it directly impacts the industries and plays a major role in the final output of the other criteria. It is impossible to utilize resources to their full extent without educating and training employees on the correct usage of leading smart technologies. Man-machine interaction, wastage prevention, and smart infrastructure and equipment are affected significantly by the organization's current policies. Therefore, the service and policy framework deserves to be at the forefront for moving towards SOM.

The industrial ecosystem achieved the second-highest weightage out of all the criteria, scoring a criteria weight of 0.2025, and it is also consistent with the literature review (Shayganmehr et al., 2021). The industrial ecosystem is the collection of all leading industrial technologies, such as IoT, big data, blockchain etc. that help implement I4.0 and achieve the productivity and efficiency goals. Identification of the industrial ecosystem as the second-highest weighted criteria has a high level of theoretical implications, and the technologies should be further studied individually. Shayganmehr et al. (2021) concluded that "Technical Capability," application of cutting-edge technology such as the ones stated above, was the most significant enabler of I4.0. These advanced technologies help integrate man, machine, and processes to create a value chain, increasing the reliability of the system (Devi et al., 2020) and making it more resilient. As stated before, this can only happen with the service and policy framework at the helm, driving all I4.0 technologies by providing employees with adequate knowledge and proper training about them.

Man-machine interaction, wastage prevention, and smart infrastructure and equipment received third, fourth, and fifth positions. As much as these three criteria are affected by service and policy framework and industrial ecosystem, they also have their significance in implementing I4.0 and CE and have theoretical and managerial implications. Man-machine interaction looks to integrate the physical and the virtual system using human knowledge and expertise on the subject to develop effective and efficient communication (Lardo et al., 2020). In any enterprise, achieving flexibility is considered a major goal, and reshaping the roles of human operators in conjunction with automated machines to improve their codependence will help meet this demand (Aceto et al., 2019). Following this, smart infrastructure and equipment need to be introduced. I4.0 technologies are not fully developed and integrated yet, causing the implementation of I4.0 to be a distant goal (Nakayama et al., 2020). Better infrastructure and equipment will help provide the necessary base for these technologies and ensure a smooth flow towards increased production efficiency. This brings us to wastage prevention. The I4.0-CE nexus helps us collect and monitor data, allowing us to use the knowledge gathered to reduce wastage generation and effectively use our resources (Tet et al., 2021), unequivocally improving the process efficiency. Adopting these practices will undoubtedly help us attain SOM and move towards a resilient future.

The results of PF-CoCoSo highlight the enablers that should be given the highest priority to move towards our final goal of achieving sustainable and resilient operations management. Product lifecycle management secured the highest priority, ranking as the most important enabler. PLM is an essential aspect of both I4.0 and CE and can be defined as the systematic and pragmatic way of controlling the whole start to finish cycle of the product to create a value chain for the customer while servicing the needs of the business (Menon et al., 2016). A proper grasp on the entire lifecycle of the product will allow organizations to introduce I4.0 technologies at any stage and use raw materials that sit well with CE ideology. Having a say in the consumption stage of the lifecycle will help companies design better products, improve the processes involved, and ensure that the end of the cycle can be extended as much as possible. PLM also sits well with sustainability goal number twelve (Responsible Consumption and Production) and will help drive us towards sustainable practices.

Internet of things scored the second-highest priority. IoT is one of the most capable and critical technologies of I4.0 and helps increase process efficiency and reduce inventory (Devi et al., 2020). It is one of the main I4.0 pillars that help digitalize CE and offer support to new lifecycle management strategies (Rosa et al., 2020). The adoption of IoT has a significant contribution in moving towards sustainability as it helps us to improve on our data collection ability and increase the accuracy and precision of manufacturing systems while at the same time also reducing resource wastage (Rajput and Singh, 2019). IoT can help connect machines to companies and humans using cyber-physical systems to open new channels and give way to interoperability (Jabbour et al., 2018). It will improve the communication between organizations and the new technically advanced machines, enabling resilience in the future.

The third rank was obtained by another key technology of I4.0, namely big data. IoT, as mentioned previously, allows for the exchange of information between systems, which can generate a large amount of data. Big data can help organizations properly analyze this data and provide us with inputs on improving the processes. Big data can be used to improve product design and development and demand forecasting by analyzing the large volume and variety of data available to an organization (Jabbour et al., 2018). It can lead to increased product lifecycle and reduced energy consumption through the possibility of predictive maintenance and optimized process sequences and travel routes (Sapltini et al., 2021). If employed correctly, it can provide industries with a highlighted path to untapped markets through existing user databases, provide a better customer experience, and help the companies become more resilient.

Our analysis led to identifying horizontal and vertical integration as the fourth-highest priority. Vertical integration includes the top to bottom integration of all company activities, from basic elements to the highest operation levels. On the other hand, horizontal integration refers to fusing external factors such as customer and supplier relations, operations management, etc., into the organization (Lara et al., 2020). Any organization that looks to implement I4.0 needs to assess its readiness in terms of Horizontal and Vertical Integration. It uses proper channels to ensure a smooth flow of materials and information within the organization and establishes clear communication with outside sources. The integration of all processes involved will allow companies to develop better policies, higher opportunities for man-machine interaction, use new technologies, smart machines, and equipment, and increase resource utilization. It makes horizontal and vertical integration a key player in all aspects.

Employee training received the fifth-highest ranking in the priority list. As the name suggests, it refers to educating the workers on new opportunities to maximize efficiency. I4.0 is still relatively new, and hence there lingers a lack of knowledge about the technologies. Regular training sessions can lead to increased employee awareness and a higher level of participation, making them better equipped and comfortable in working with these techniques (Shayganmehr et al., 2020). Lack of technical knowledge hampers the industry's ability to improve their environmental performance, and insufficient technological know-how will lead to the technologies not being adopted (Rizos et al., 2016). Employee training is a direct sub-enabler of service and policy framework and helps achieve sustainability and resiliency in operations management.

4.1 Theoretical Implications:

The study has combined I4.0 and CE by analyzing and prioritizing their enablers for achieving SOM. The results generated using the novel 4 stage hybrid framework provide the authors with a way to suggest recommendations for adopting I4.0 and CE for SOM. The study revealed service and policy framework and industrial ecosystem to be the highest weighted criteria, and the top five enablers are product lifecycle management, IoT, big data, horizontal and vertical integration, and employee training. Implementing said criteria and enablers would help industries achieve the sought-after goals and allow them to take steps towards corporate sustainability, earning the goodwill of the customers and stakeholders. Control over the product lifecycle will allow organizations to minimize wastage and implement a circular economy which would sit well with their corporate social responsibility goals. Proper marketing strategies will help earn existing customers' appreciation and expand their customer base (Chang et al., 2017). A firm committing to multiple prominent changes for building resiliency and ensuring its survival showcases effective managerial organization and is in accordance with the stakeholder theory. The key stakeholders usually include the customers, employees, shareholders, suppliers, communities and governments. Improved product lifecycle management will allow companies to introduce sustainable parts in the product. This will help create awareness among the customers, driving the growth of the sustainable products market and also provide consumers with the choice of willingly contribute to the sustainability of the Earth by choosing a much more eco-friendly option. The employees will also benefit from the integration and implementation of I4.0 and CE as the training provided to them by the organization will improve their skills and make them more advanced in handling the latest technologies, thus providing them with new opportunities to update themselves which otherwise is not available normally. The horizontal and vertical integration takes into account not only the whole organization but rather also includes the suppliers and customers, which means that I4.0 technologies such as IoT and big data analytics can help in increasing the response time of supplier business communication and also help in reducing inventory, thus reducing costs. However, the relation is bi-directional and in order to be able to improve the communication and information sharing, there first must be technology and knowledge sharing. Thus, the industries that want to implement the I4.0-CE nexus, must also help their suppliers in implementing the same level of technological advancement, thereby increasing the trust and encouraging the relation between supplier and firm. Similar to customers in generating demand and suppliers in providing supply, the governments also play a crucial role and act as a shareholder for the company. A highly efficient and sustainably operational company will undoubtedly be of beneficial standpoint from the government's viewpoint as the company will not only provide employment but also be highly environment friendly in conducting its operations, which will drive other competing organizations to adopt similar standards and drive the nation towards sustainability in all three aspects: economic, environmental and social. Last but not the least, the shareholders will also benefit from this expedition as the company will become technologically advanced and produce sustainable products in a sustainable way, improving the social image of the company and driving its shares up. In this way, the industries can also take advantage of said theories to improve their market image.

4.2 Managerial Implications:

The order of rankings of the stated criteria and enablers can be linked to the achievement of our objectives, and along the lines of said results, the following themes are recommended that can be worked upon to move towards a sustainable and resilient era of industry.

Recommendation 1. The government needs to extend support to industries in laws and legislation that need to be enforced to help adopt I4.0 and CE.

Lack of governmental support and policies is regarded as the most significant strategic challenge in transforming traditional industries into future industries. Government help will allow business organizations to rapidly adapt and adopt (Luthra and Mangla, 2018), making themselves sustainable and resilient. An example case study by Ranta et al., 2018, shows that China, despite having high-level CE laws, cannot benefit from it because of the lower level of implementation and enforcement of these laws at a local scale. Residents on the lower spectrum of income charts rely on selling recyclables, and hence there is a difficulty in generating regulatory support for CE. A similar suggestion was given by Lieder and Rashid, 2016 where in their work they proposed a concurrent approach in which the government and industries work alongside for achieving CE. Governmental institutions tend to think about the environmental aspects whereas industries, in spite of being aware of the environmental affects of their operations, cannot take steps due to competitive pressure. Better policies and extended government support will help end these woes and enable industries to adopt I4.0 and CE.

Recommendation 2. Provide seminars and training to employees in using I4.0 and CE techniques.

Prior knowledge of any technology is necessary for its proper implementation. The employees are the workforce of any organization and are the ones that must encounter these technologies on a day-to-day basis. Without proper knowledge and training, they are likely to feel alienated by these changes and will soon find themselves disapproving of them. Hence, providing proper training to them is a necessity. A case study to identify the barriers to sustainable I4.0 in the footwear industry by Narwane et al., 2021 revealed that lack of skilled and trained workforce and lack of awareness about I4.0 are some of the leading influencers in the industry's inability to implement these technologies. They further discussed how workshops and training sessions need to be provided to employees to overcome the hurdle of implementing I4.0 and CE. Margherita and Braccini, 2021 performed a case study on an Italian ceramic products manufacturing firm which successfully adopted I4.0. The main takeaway from the case study remains the positive outlook of the workforce regarding the changes made in the traditional practices. This could only be possible due to the proper discussion and guidance from management side to the employees and further the courses and training offered by the firm to help the workers acquire the necessary skills.

Recommendation 3. Organizations need to incentivize the workers to partake in adopting new technologies actively.

As much as knowledge and training of employees are necessary for industries to realize the potential of I4.0 and CE, the workforce needs to be provided with incentives to participate in such training programs. Active participation from top management to reward the workers' positive behavior will help strengthen the bond of the employees with these new technologies and techniques and help improve the performance of industries.

Recommendation 4. Proper lifecycle monitoring must be ensured to achieve sustainable production and consumption cycles.

One of the key ways of achieving CE is by addressing the issues of product lifecycle management. A higher level of control over the product's entire lifecycle will help ensure that the materials used for production follow CE and have reuse and recycling capabilities. The close monitoring of the lifecycle will also help reduce the amount of wastage in any stage from conception, design, and production to end of life. Rosa et al., 2020 in their work have concluded that I4.0 technologies such as IoT, AM, CPS etc. can help in achieving CE. According to them, IoT can help integrate digital manufacturing and product lifecycle management, while CPS works on better management of CE practices on the shop floor. AM can also be used as an added benefit to improve the product design and ensure better material utilization.

Recommendation 5. Optimize process efficiency by applying IoT and big data to collect and analyze data.

IoT and big data are the two main pillars of I4.0. Even though both are self-sufficient in improving any industry's efficiency, their combined application magnifies their effects and opens pathways to a higher degree of optimization. Belhadi et al., 2021 in their study, revealed how the Covid-19 outbreak caused global supply chains to shut down and showcased the quick thinking of the automobile and the airline industry in readjusting their efforts and resources towards BDA to get real-time information and overcome the challenge posed to them. SOM can be achieved by using IoT and big data as the key drivers for data collection, analysis, and sharing. Abdul-Hamid et al., 2021 in their work have identified improvement of real time performance as one of the key drivers of enabling I4.0 driven CE. They discuss about how improved connectivity, forecasting and other techniques can help improve process efficiency and maximize profits. IoT and big data if employed correctly can help organizations establish new and improved processes, reduce downtimes and optimize their operations.

Recommendation 6. Business models that allow for horizontal and vertical integration should be followed.

If any firm's prior knowledge leans strongly towards either side of the technological or customer-based content scale, then the chances are that the firm will not be able to develop innovative BMs and partnering with external factors will help avoid such situations by bringing back balance to the ideology (Paiola et al., 2021). In the case study of Dwivedi et al., 2021 for responsible footwear production in a big data-driven world, the authors state that the involvement of suppliers and customer awareness around sustainable practices will support the achievement and implementation of sustainability. It directly correlates to the horizontal integration model involving customer and supplier input. Similar results were observed in the work of Lieder and Rashid, 2016 where they concluded that there is a need to develop innovative business models by developing new partnerships and integrating remanufacturing practices to improve on current models.

Recommendation 7. Adoption of I4.0 technologies and investment towards proposed enablers will pave the way to a sustainable future.

Sustainable manufacturing supports the highly effective use of resources and wastage minimization; I4.0 technologies help optimize processes – reducing waste and increasing efficiency. Thus, I4.0 and sustainable manufacturing have similar objectives, and implementing I4.0 will lead to sustainability (Dixit et al., 2022). Capital investment towards proposed criteria and enablers is necessary to implement I4.0 and CE towards sustainable operations management. Many studies have proposed adoption of I4.0 due to its economic benefits. Abdul-Hamid et al., 2021 in their study also evaluated economic attractiveness as a key driver, however, they advised the industries to evaluate their current situations before taking any steps. The current study has worked on the integration of I4.0 and CE, hence, investment towards the proposed enablers will not only help firms adopt I4.0 for their economic gains but also ensure improved CE measure to move towards sustainability.

5. Conclusion, Limitation, and Future research direction

I4.0 was introduced in 2011 to usher in the new era of digital manufacturing, and with it came many technological advancements. New technologies like IoT, big data, cloud manufacturing etc. came up for helping advance the digitalization and automation capabilities of the industries. However, the industries got swept away by these new technologies, and little to no attention was given to sustainable practices. Today, the effects of such practices are visible, and it has caused everyone across the globe to search for solutions to this problem. The search for this problem brought forth CE. CE refers to the circular approach that emphasizes on repairing, remanufacturing, and reuse of the product as well as improving the utilization in a way such that one person's waste can act as a resource for the other. Combining I4.0 and CE brings forth the pathways to achieve sustainability and resiliency. This study integrates these concepts to put forward various implications as well as recommendations that can be adopted to move towards our goal of SOM. A novel hybrid methodology has been adopted for the study. After successful identification of the enablers, Pythagorean Fuzzy Delphi approach was used to validate the findings. Secondly, Pythagorean Fuzzy AHP was applied to find the criteria weights and these criteria weights were used in the next step of PF-CoCoSo to find the rankings of the enablers. The results were also checked for robustness using sensitivity analysis. The major highlight of the research has been the identification of service and policy framework as the significant criteria, along with the identification of product lifecycle management as the leading enabler. The selected criteria and enablers positively impacted the I4.0-CE nexus, with some being higher than others. IoT for data collection and process monitoring, big data for analysis of the collected data, horizontal and vertical integration for smooth flow of materials and information, and employee training to make employees more equipped in working with the new technologies were the other key identified and highest rated enablers. Another major takeaway from the research has been the interdependence of all the criteria. Any change in service and policy framework also directly or indirectly impacts the industrial ecosystem, man-machine interaction, wastage prevention, and smart infrastructure and equipment. Investing in the highlighted criteria and enablers will help achieve a sustainable and resilient future.

5.1 Limitation and Future research direction

In any research, there always exists some natural area for ambiguity. The authors have done their best to limit this ambiguous nature by applying a hybrid 4 stage framework that involves techniques such as PRISMA method for selection of choicest articles, PF-Delphi for identification and validation of criteria and enablers, PF-AHP for criteria weightage calculation, PF-CoCoSo for ranking of enablers and sensitivity analysis for checking the robustness in results. The strategy adopted identified service and policy framework and industrial ecosystem as the essential criteria for implementing I4.0 and CE to attain SOM. However, there are still certain limitations to this approach. The conceptualization of the criteria is subjective and one of the areas where this can be seen. The other area is the judgment of the experts. Every expert has their ideology of the concepts discussed, and it is crucial yet challenging to get an unbiased rating. Another shortcoming can be seen in the lack of confirmatory analysis. However, sensitivity analysis was done to at the very least check the framework for robustness.

Despite the limitations, this study has put forward a quantitative result to adopt I4.0 and CE to achieve SOM, producing scope of future research. The criteria defined can be further studied individually to attain knowledge of their impact on every industry sector. Also, further research can be conducted to redefine and refine the criteria definition, expanding the scope and allowing for better future investments. However, the study effectively ranked the enablers, providing the industry with a basic priority list to help us move towards a more sustainable and resilient operations management.

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