Can Industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers

ABSTRACT. The ever-changing times demand a resilient industry that quickly adapts to the oncoming wave of new technology; however, a strong social environment that comprises organic social values is needed for a thriving human society. Industry 4.0 has become the standard for applications in recent years, as its technologies are rapidly being implemented and positively impacting every sector. However, these developments are still unable to achieve the desired outcomes and have neglected the environment by prioritizing machines over humans. Therefore, the Industry 5.0 (I5.0) revolution is a call to bring forth the ideas of sustainability into practice, integrate human values with technology, and is considered a step forward for achieving sustainable development goals. Hence, the present study proposes a framework for analyzing I5.0 enablers for achieving sustainability by integrating human values with technology. To achieve the objectives, this study was conducted in three different phases: 1) through extensive review, the list of criteria and enablers was identified; 2) Pythagorean fuzzy Delphi was used to validate the enablers against criteria; 3) a hybrid approach of Pythagorean fuzzy analytical hierarchy process-combined compromise solution was employed to calculate the weights of selected criteria and determine the ranks of enablers. A sensitivity analysis was then performed to check the robustness of this framework. The findings show that the criterion of personal customization obtained the highest weight followed by human-machine collaboration, which will create a smart cognitive environment for humans. Human intelligence is used in more important places, which will help society focus on developing social values. The authors also put forward seven propositions about adopting I5.0 enablers for best results, taking examples from existing case studies and helping industrialists adopt I5.0 methods.

Keywords:Industry 5.0; Sustainable development; Bioeconomy; Human–robot collaboration; Mass personalization; Pythagorean fuzzy

1. **Introduction**

Human civilization has gone through many industrial revolutions starting from the mid- to late eighteenth century [1]. The journey of an ever-evolving industry went through different phases, each producing a higher level of technology. In this manner, technology and technical know-how have kept evolving with changing times. As humans have progressed throughout history, each study in advancing science has led to industrial revolutions at different periods. The first industrial revolution, Industry 1.0, began around 1760s and was powered by fossil fuels and steam machines. The second industrial revolution, Industry 2.0, was triggered around the 1840s with the breakthrough of electrical power. Industry 3.0 began in the 1960s with the age of computers, transistors, and later silicon chips and advanced electronic devices. Industry 4.0 has brought in technologies like artificial intelligence (AI), cloud computing [2], the Internet of Things (IoT), and many others [3,4]. In the last few years, scholars have made progress toward implementing the fifth phase in this journey, Industry 5.0 [5]. This phase focuses on concepts of sustainability, bioeconomy, and a collaborative environment of technology and human beings [6], thus establishing a resilient industry that incorporates human social values.

Industry 4.0 introduced many technologies into mainstream manufacturing and other industries, including the Internet of Things (IoT), artificial intelligence (AI), augmented reality (AR), etc.; today, these technologies are extensively implemented throughout engineering, business, healthcare, and service-based enterprises [7,8]. These ideas have remained the center of attention in industry over the last four to five years [9]. However, these have also enhanced and advanced our industrial and other nonindustrial processes, although specific issues remain prevalent, e.g., mass customization and personalization [9], complete automation, proper systems for performing re-iterative jobs [5], all of which are difficult to achieve. The business environment is fast-moving and adaptive with upcoming technological developments and becoming denser and competitive in the progressing era of globalization [10]. This calls for new innovative approaches to be implemented in existing and upcoming ventures to establish solid resiliency and sustainability within the business and industrial sectors [11].

Moreover, humans face an alarmingly urgent need to change practices as climate change continues to advance at an ever-increasing rate. Pollution of the environment and rapid consumption of nonrenewable resources are degrading the planet. New diseases are on the rise [12], the disruption caused worldwide by the COVID-19 outbreak being the latest. This situation offers enough evidence that current practices must be changed now and aim toward taking a more resilient, bio-centric approach, such as through medicine and surgery [13], agriculture, and food [14], renewable energy, green energy, bioengineering [15]. There is a need to shift toward sustainability [1] in every part of our lives; toward a resilient, sustainable, and bio-oriented [16] industry and integrated society, where human values [17], socio-industrial synergy, our environment, and our planet are preserved. These issues have led to the wake of a new industrial revolution, i.e., Industry 5.0, which can be collectively understood and compared with the idea of Society 5.0, originating in Japan [18]. This revolution is subjected to deal with every aspect of technology and human lives that could not be covered in Industry 4.0. A significant increase and enhancement in scalability, flexibility, resiliency, and efficiency will be observed with it [19].

By performing this study, the authors put forward their contribution to the cause and lay a foundation for future research to proceed in a proper direction [20]. Every new concept comes with attractive benefits; at the same time, however, there are several issues to address. Whenever a new concept is introduced, experts in academia as well as industry are faced with the challenge to test its feasibility in a functioning scenario. It is suggested that, for realization of the acceptance of a concept and its practical application, the right and most applicable methods that enable its implementation must first be identified. Then, every aspect of its working must be assessed in its quality, quantitative and mathematical study, and financial and economic influence. These ideas have led the authors to perform the current study and put forward their take on this uprising of a sustainable and resilient industry and society with social value creation, in terms of Industry 5.0. Therefore, this study seeks to identify certain enabling technologies (enablers) for Industry 5.0 that would promote these social and resiliency factors. In doing so, deployers need to determine the priority of adopting them in the industry. Thus, the authors raise the first research question (RQ):

RQ-1: What are the main criteria of focus in Industry 5.0 that promote resiliency and social value creation?

The authors have dealt with ambiguous and incomplete data to answer the above RQ. The authors have also performed an extensive literature review and rigorous investigation of previous studies. Understanding these studies has helped in identifying the areas of shortcoming in Industry 4.0 for a needed level of resiliency and human value integration [21], both conceptually and in terms of quality. It is thus necessary to perform a quantitative analysis of the same to validate the proposals mathematically.

These criteria have originated because further development in these domains is needed, which can be initiated by integrating qualified enablers into the concerned venture. This brings us to our second RQ:

RQ-2: What are the most important enablers of Industry 5.0 that would will be made possible with the effective collaboration of human intelligence and technology?

To address RQ-2, further study of the previous literature has been conducted. Previous studies in the field led us identify important technologies that must be integrated into the industry as well as practices that must be adopted to guide humanity toward a sustainable future with resilient industry and social value synergy [22,23]. This will be made possible with the effective collaboration of human intelligence and technology.

However, there is still a need to quantitatively validate as well as prioritize these enablers. Mathematical validation is essential when it comes to proposing new enablers for the industry. Hence, the authors raise the third RQ:

RQ-3: How can the relative and overall importance of these criteria and enablers be assessed and priority of focus established for the current theme in implementing Industry 5.0?

To acknowledge the above RQ, the authors propose a phase-wise methodology consisting of three phases. The first phase deals with the identification and selection of the enablers. This is done by circulating a research questionnaire to collect experts' data and then assessing the enablers based on the data, quantitatively using the Pythagorean fuzzy Delphi (PF-Delphi) method. The selected enablers are then ranked using a combined framework of the Pythagorean fuzzy analytic hierarchy process (PF-AHP) technique and Pythagorean fuzzy combined compromise solution (PF-CoCoSo) method [24], in second and third phase respectively. A sensitivity analysis is then performed to validate the results. Fig. 1 shows the step-by-step process of the research process.

3.1 Pythagorean Fuzzy Sets

1. Introduction - construction of problem structure, research question and research objectives

2. Literature review

2.1 Identification of the key Criteria and Enablers of Industry 5.0

2.2 Understanding Industry 5.0 revolution

2.3 Problem definition and research highlights

3 Research methodology

Phase-1 Study

3.2 Questionnaire development and data collection for using Pythagorean Fuzzy Delphi

3.3. Questionnaire development and data collection as per given scale in Table 4

Phase-3 Study

4. Performing Analysis and 5. Results and Discussion

6. Theoretical and Practical Implications of the study

Enabler Rejected and dropped

Enabler Accepted

Calculate the weight of criteria using Pythagorean Fuzzy AHP

3.4 Calculate the priority rank of enablers using Pythagorean Fuzzy CoCoSo

7. Conclusion and limitations of the study

Phase-2 Study

**Fig. 1.** Phase-wise research flow chart.

The main contribution of this study is as follows:

* This study highlights the regions of focus in resiliency of industry and social values in Industry 5.0. Forming conceptual models of industry and enterprise [25] has played a crucial role in Industry 4.0 and will be equally important in Industry 5.0. This will be beneficial for scholars and industrialists to direct their future work.
* The enablers will be ranked and proven mathematically. The authors have conducted a stepwise qualitative as well as quantitative analysis using novel, powerful Multi-Criteria Decision Making (MCDM) techniques, such as AHP, in a Pythagorean fuzzy environment, which considers impreciseness of data with better efficiency [26]. This will give a prepared list of technologies with the most to least importance. The concerned individual can thus decide which he or she should pick up and/or invest in.
* This study introduced a novel framework, which combines the four steps involved to address any MCDM problem: selection, weightage, ranking, and validation. For selection purposes, the Delphi method is utilized using Pythagorean fuzzy numbers (PFN) to deal with inaccuracies in decision-making. For weightage of criteria, PF-AHP is utilized; for ranking our enablers, the PF-CoCoSo method is utilized with weights obtained from PF-AHP. A sensitivity analysis is also performed to validate the proposed framework.

The results of the analysis will provide the most necessary criteria of consideration and the most appropriate enabler for establishing resiliency in the ongoing development of industry–society collaboration [20]. Good resiliency can only exist once people are incorporated in areas where the human touch is essential and has been either disregarded or lost under mechanization. The suggested criteria and enablers, in subsequent order of priority, can be considered for implementation, which would be significant in reversing the damage done to the environment and restoring the human social factor [21], thus forming a better, more resilient industry and preserving social values within society.

The present study is structured as follows. Section 2 provides the literature review. In Section 3, the used methodology is explained. Section 4 gives a detailed analysis of the results and phase-wise conduct of the study, with sensitivity analysis. Section 5 and 6 discuss results and the implications in theoretical and practical views, respectively. Section 7 provides the conclusion and limitations of this study and recommendations for future research.

1. **Literature review**

This section contains the required literature on Industry 5.0, focus of Industry 5.0, definitions of the deduced criteria, theoretical information of the enablers, and research contributions made by this study. It also highlights issues that might be faced in establishing Industry 5.0.

* 1. *Appropriate article selection*

Accordingly, there was a need to assess the existing literature and discover the texts addressing our agenda. Formerly, a search on research papers and articles was performed on Google scholar and Scopus profile. The only aim of this article selection was to focus on the quality content to be presented in the study. Some of the keywords used for finding appropriate articles were “Industry 5.0”, “Social Value”, “Enablers of Industry 5.0”, “Industry 5.0 Technologies”, “Resiliency in Industry”, “Sustainability through Industry 5.0”, “Bioeconomy”, and “Mass Customization”. The former search brought 90 research papers and 15 articles. The articles chosen for this study fall under the time horizon of 2016–2021. Further, apart from journal articles, background papers and short reviews were also studied individually and added during the article selection process. During finalizing, the research papers and articles were sorted by filters for, e.g., insertion of only journal articles and removal of duplicate articles on search databases; most appropriate ones (58) were considered and studied individually to determine their significance for the present research. In this context, five criteria and 15 potential enablers (as shown in Fig. 2) for Industry 5.0, along with their impact on the next industrial revolution, were shortlisted and aligned in an Excel sheet for a final assessment. The listed enablers were confirmed through experts' feedback [27]. A brief description of literature-supported criteria and enablers is given in Tables 1 and 2, respectively.

These enablers might hold some uncertainty from the assessment. Human judgment is contextual; ambiguities will be involved and contradiction in justification. Therefore, there is need for a justified quantitative result, for which the authors introduce the PF-Delphi method for a quantitative selection of our enablers. Our listed enablers are fed to the PF-Delphi algorithm to quantitatively check for their acceptance, based on the experts' opinion in the form of a questionnaire, which is circulated among the panelists. This process is discussed in detail in Phase 1 of performing the analysis (Section 4).

* 1. *Industry 5.0 revolution*

The objective of Industry 5.0 is to establish sustainability and environmentally friendly [28] methods and to enhance existing work and service experiences. It has the vision of collaboration between humans and robots and advanced digital systems, thus forming a smart environment. It promotes bioeconomy [29], thus encouraging developments in healthcare, medicine and surgery [30], genetics, and biosciences and incorporating products of agriculture [31], forests, and animal resources and farm activities [14]. The concepts of Industry 5.0 express an optimum utilization of resources [5] as compared with Industry 4.0. However, certain issues exist with any newly introduced concept. Some negative issues with Industry 5.0 include legal and regulatory issues with robots, preference of working with robots, psychological issues, human-to-human communication gaps [32], and employment issues.



**Fig. 2.** Enablers of Industry 5.0.

**Table 1**

Criteria of assessing Industry 5.0's enablers.

|  |  |  |  |
| --- | --- | --- | --- |
| Criteria | Description | Impact  | References |
| Customization (C1) | The customer selects from a growing menu of options. This set of options is perfectly configured and arranged. They desire mass personalization, which can be obtained only when the human touch is restored to manufacturing. This is what Industry 5.0 is all about to being social value to the industry.  | Mass personalization of product/services in technical and another sector results in industry, human value synergy robustness and resiliency. | [6,33]  |
| Human–Machine Collaboration (C2) | Computers work alongside human intelligence, autonomous machines, and collaborative robots, equipped with sensors that will make them more active to the people working nearby. | Smart environment, redundant jobs being performed by machines, human calibre used in for better tasks. | [5,32,34,35]  |
| Bioeconomy (C3) | Bioeconomy, the second vision of the fifth industrial revolution is defined as the conversion and production of renewable biological sources into value-added products like food, bioenergy, bio-related products. These include agriculture, forestry, and fisheries as well as some parts of chemical, biotechnological, and energy industries. | Bio-oriented, sustainable economy, increased business in biology-related fields, initiated economic growth and resilient development of industry. | [5] |
| Sustainability (C4) | Sustainability of products will lead to more utilization of products; it will also put control on waste generated by manufacturing industries. | Better utilization of resources, preservation of society and environment. | [31,36]  |
| Business and Finance Administration (C5) | Most companies will look for attention-seeking innovation, but a uniform flow of gradual innovations can be more profitable. Smaller innovations will be easier to generate and test in the market. | New business opportunities, better financial development. | [6,19,37] |

**Table 2**

Enablers of Industry 5.0.

|  |  |  |  |
| --- | --- | --- | --- |
| Enablers | Description | Impact  | References |
| Bionics (A1) | It is the science of building artificial systems that have characteristics of living systems. It is the technique of imitating nature. It is not about copying nature but understanding how things work in nature. It can help in making a healthcare industry resilient.  | In orthopaedics, healthcare, medicine, surgery, and chemical industries. | [38–40]  |
| Sustainable Agricultural Production (A2) | Considering the environment, new technologies are entering the agricultural sector to keep up the sustainability of farm production, which is towards social value. | Better methods of resilient production, preserving land fertility, and removing pollution. | [14,23,31,41] |
| Cyber Physical Systems (CPS) (A3) | These are computer systems in which computer-based algorithms monitor a mechanism. CPS consists of people, AI, and physical systems well connected through high-speed Internet, making our industry resilient.  | Complete industrial and transport automation for more robustness and flexibility. | [42–45] |
| Virtual Reality (VR) (A4) | Virtual technology is the computer-generated 3D environment where a person can experience a virtual world, totally different from the real world, using electronic devices like special goggles with a screen or gloves fitted with sensors. It is one of the enablers enabling our industries from sustainable to resilient.  | Enhancing simulation and prototyping in engineering and physics. | [46,47]  |
| Green Computing (A5) | Green computing is defined as a technique of using computer systems in an eco-friendly manner. It is the study of designing, manufacturing, and disposing of computer devices with the motive of reducing environmental effects. | More bio-oriented and sustainable computing. | [47–49] |
| Digital Twin (A6) | It is a digital representation of an object. It is often a digital replica of an object within the physical world, like a reaction-propulsion engine, wind farms, or more oversized items like buildings or even whole cities. It directly helps the industry to reduce the sample production cost, which helps in creating the industry as resilient. | Enhanced resiliency in industrial planning and simulation.  | [50,51]  |
| Waste Prevention (A7) | It means the reduction of waste-generating practices, recognizing new opportunities, reconsidering techniques, reusing and recycling materials. Waste reduction or reuse is one step towards industry sustainability.  | Refusal and removal of intoxicating practices, materials, and byproducts. | [36] |
| Big Data (A8) | It can be defined as large amounts of data, both structured and unstructured, usually stored in the cloud or in data centers, then utilized by companies, organizations, start-ups, and even the government for different purposes. Proper utilization of big data helps the industry accurately predict customer demand, which helps them be resilient.  | Enhanced resiliency in customer service and more freedom of mass-personalization. | [43,44,52] |
| Smart Materials (A9) | Smart materials, also called intelligent or responsive materials, are designed materials with one or more properties that can be significantly changed in a controlled fashion by external stimuli and changes. Smart materials include self-healing material that can directly or indirectly help society overcome daily disruptions.  | Applicable in defence, medical, manufacturing, automotive industry, etc. | [6] |
| Holography (A10) | Holography is best known for generating three-dimensional images, but it also has a wide range of other applications. It may be an effective instrument for completing high-precision measurements which make industry resilient. | Integrating possibility of 3D visualization in space, especially human visualization. | [9,30,53] |
| AI-based Management Systems (A11) | It means artificial intelligence can be implemented in hospitals, hotels, education, airports, railway, reservation systems, and public transport management systems. It helps the industry to take management decisions more precisely without emotional interruptions.  | Ease of management, better handling of re-iterative jobs, better service. | [29,44]  |
| Renewable Energy Sources (A12) | There are vital renewable energy sources are available such as Solar energy, wind energy, tidal energy, nuclear and plasma energy, geothermal energy. It can help the industry to enter next-generation 5.0.  | Reverse the damage of fossil fuel emissions, reach sustainability goal seven. | [54,55] |
| Advanced Simulation (A13) | Hybrid simulation systems, augmented reality-based simulation, reaching and scaling parts would otherwise be indeterminate. Industry 5.0 will focus on advancing simulation to be an integrated part of manufacturing processes and other prediction systems, which helps make resilient systems. | Improved simulation methods to produce more resilient, sustainable designs. | [9,56]  |
| Fin-tech (A14) | Bringing in digital currencies, digital transaction systems, stocks, and financial investment systems enables exchanges in real-time. | Fast, secure, resilient digital systems, improved digital transactions. | [43,57]  |
| IoT-Enabled Systems (A15) | IoT is input in many industrial and commercial systems and frameworks. With the invention of better networking (e.g., 5G), IoT is manifesting. Systems like IoT in shopping, e-commerce, smart factories, home utilities, etc., are the next generation of IoT-enabled systems. | Ease of control over systems, with remote accessibility. | [2,4,6,58–60] |

Industry 4.0 has been thriving in introducing many next-generation technologies such as AI, IoT, Internet-based services, digitalization of banking, finance [37,61], transactions, retail, sales, and businesses. Manufacturing has been scaled to a great extent. Services have become more user centric. As previously stated, however, Industry 4.0 has missed out on some major aspects of manufacturing, services, and society and the environment [62]. For instance, customization is made possible largely because of advanced software, but mass customization has yet to be achieved [10]. Similarly, simulation techniques and software are being adopted [56], but they are still far from the potential that they hold to serve. An extensive knowledge of application is necessary for solar energy in areas facing energy crisis; however, the technology remains to be heavily deployed in those regions.

Thus, there is a lack of desired resiliency in development seen through Industry 4.0. Adoption of concepts of Industry 5.0 will lead us to a better future, with resources being better utilized. Renewable energy [55] and green energy will lead us to reduce carbon emission level manifolds and ease global pressure placed on fossil fuel reserves all over the world. Because these resources can be brought in rural scenario and regions with inadequate power setups, they have potential to solve the world's energy crisis. An extent of social sustainability can be thus expected to be achieved. Industries such as agriculture [41], animal farms, and forestry are still rated as being small-scale and rural, even though they contribute a great amount to the agro-based economies such as India's. For a bio-oriented atmosphere, there is a need to upscale these industries as well. There is a high scope of research and development in engineering for medicine and surgery [38]. This field incorporated many innovations to improve healthcare. These fields are on different platforms but must be focused collectively for moving toward a green, resilient, bioeconomy. Finally, these measures are set to be effectively induced into society itself, with a vision where humans and collaborative robots [35] work together, where highly effective AI manage the reiterative systems [44] and where high-quality facilities, products, and assistance are available in a green, healthy, and smart environment so as to preserve nature and human values for the generations to come. In this way, human beings shall progress toward overall sustainability of civilization and our planet.

The research in this direction thus far vaguely identifies and categorizes the required enablers, as shown in Fig. 2, which will help us reach the goals. Therefore, there is a need to select crucial enablers and prioritize them for a clearer scenario.

1. **Methodology**

This section provides the applied methodology for selecting the enablers based on proposed criteria and then ranking them according to their calculated weightage. This is done in three phases (as shown in Fig. 1).

* 1. *Pythagorean Fuzzy Sets*

Pythagorean Fuzzy Sets (PFS) were introduced by Yager [64] in 2013. Like Fuzzy Sets, these sets deal with the vagueness in selection and provide flexibility of reasoning as per human standards. These sets take into account inaccuracies and uncertainties in the decision-making process. A Pythagorean Fuzzy Set is described as:

P = {< x, $μ\_{P}$(x), $ν\_{P}$(x) >|x ϵ U}
$μ\_{P}$(x) ϵ [0,1]
$ν\_{P}$(x) ϵ [0,1]

$$0\leq μ^{2} + ν^{2}\leq 1$$

PFSs are an extension of Intuitionistic Fuzzy Sets (IFS) and are governed by a membership function (μ) and a non-membership function (ν). Furthermore, a Degree of Determinacy (π) is also defined that includes the unclear selections that are not in the membership or in the non-membership function and are defined as:

$$π=\sqrt{1-μ^{2}-ν^{2}}$$

Classical fuzzy sets define $=1-μ$ . This limits the domain of fuzzy sets to a certain relation.

However, the non-membership function ν may not necessarily be equal to 1 – μ, considering human evaluation. Furthermore, varied non-membership values would lead the sum of membership and non-membership functions to exceed 1. PFS resolves these issues by expanding the domain of fuzzy sets. This is described graphically in Fig. 3.



**Fig. 3.** Graphical representation of PFS.

*3.2 PF-Delphi*

The Delphi method is an effective tool for risk analysis [65], as well as for selection/rejection of appropriate members from a given collection of data. The Fuzzy Delphi method was proposed by Ishikawa et al. [66]. The technique uses the method of the classical Delphi method and integrates Fuzzy sets to produce decisions in accordance with human evaluation [67]. The authors propose using Pythagorean Fuzzy Sets [59] in this method to expand the domain under consideration and improve the quality of our analysis.

The steps proposed in the PF-Delphi method are as follows:

* Step 1: In this step, different enablers are identified based on the selected criteria. They are then enlisted in tabular form for the experts' evaluation.
* Step 2: The document is circulated among experts for evaluation according to their opinion. The data obtained are in linguistic terms and converted into PFNs using the scale mentioned in Table 3.

**Table 3**

Rating of criteria and enablers w.r.t. linguistic terms [68].

|  |  |  |
| --- | --- | --- |
| 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) |

Let $\tilde{A}\_{ij}$ be the evaluation score in PFN for $i^{th}$ enabler as per the opinion of $j^{th}$ expert of $n$ experts [27].

$\tilde{A}\_{ij}=(μ\_{ij}, ν\_{ij}) $ (1)

where, $i=1, 2, 3,……, m$; $j=1, 2, 3,……, n.$

* Step 3: For a combined structure, the Union operation is performed on sets obtained in each row [69].

$α=\left(\max\_{i}μ\_{ij}, \min\_{i}ν\_{ij}\right)=(μ'\_{i}, ν'\_{i})$ (2)

* Step 4: Calculate the degree of hesitancy using equation (3):

$π'\_{i}=1-μ'\_{i}^{2}-ν^{'}\_{i}^{2}$ (3)

* Step 5: A crisp value for each enabler is then obtained by defuzzifying using equation (4) [70].

$d\_{f}\left(α\right)=\frac{1+μ'\_{i}^{2}-ν^{'}\_{i}^{2}-π^{'}\_{i}^{2}}{2}$ (4)

*3.3 PF-AHP*

AHP is an effective and powerful MCDM technique and is used to solve problems involving multiple criteria of decision making [71]. The results obtained with this technique are better compared to other knowledge-based methods, such as ANP, TOPSIS, and ELECTRE [72]. The PF-AHP approach is utilized to accommodate the vagueness of and impreciseness [63] in a calculation model. It uses the methods of the classical AHP technique with the inclusion of PFN as the unit of assigning relative importance scores. It is simple to use and highly effective in application; therefore, this method is applied in the present study. The method follows the steps as mentioned by the authors of referred literature [24,63]. First, create a Pair-wise comparison matrix for criteria with respect to experts' opinions. Conversion from linguistic terms is done using Table 4. Then the Differences Matrix formed, followed by the Interval Multiplicative Matrix, between lower and upper values of the membership and non-membership functions. The determinacy value is then calculated and Matrix of Weights before normalization is generated using this value. Finally, the criteria weights are calculated through this matrix.

**Table 4**

Scale of relative importance for AHP [63].

|  |  |  |
| --- | --- | --- |
| Linguistic term | Abbreviation | PFN as IVPFN |
| $$μ\_{L}$$ | $$μ\_{U}$$ | $$ν\_{L}$$ | $$ν\_{U}$$ |
| 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 |

*3.4 PF-CoCoSo*

The Combined Compromise Solution (CoCoSo) method is a relatively new but highly result-oriented technique [73–75]. This method uses Exponentially Weighted Product (EWP) and Simple Additive Weighting (SAW) models with aggregation strategies to provide a consistent compromise solution [24]. The results obtained are consistent with the changes in weight distribution [76]. The integration PFS allows one to deal with uncertainties in decision making problems. It has great efficiency in differentiating alternatives by assigning a proper rank to each of them [77]. The process of computation is as discussed by the authors of referred literature [24]. A decision matrix is first created with the help of experts' opinion in linguistic terms, which are converted into PF-Numbers using Scale of Linguistic Terms from Table 3. Then the matrix of Score Function is generated and converted into an orthonormal Pythagorean Fuzzy matrix. The total of the weighted comparability as well as power weight comparability sequence are then calculated. Using these, the relative weights of the alternatives using aggregation score strategies are finally calculated.

1. **Performing the analysis**

In this study, the authors aim to present a set of enablers that will help implement the concepts of Industry 5.0. To understand the direction of further research and progress, the concerned concepts must be differentiated into suitable criteria [27]. Along with this, there is a need to present a quantitative analysis and prioritize our enablers. Society and industry possess the corresponding ability of research and development (R&D), based on available technology, to consider new ideas in the systems. Thus, experts from academia, the industry, and research backgrounds are required to provide the necessary opinions, along with essential points as per their knowledge. Hence, by using the snowball sampling method a panel of nine experts was selected to assess the acceptance of the proposed enablers [78]. Table 5 mentions the details of chosen experts, their fields of expertise, along their experience periods in their respective fields. The experts put forward very competitive opinions, which were then processed for obtaining quantitative results in three major phases. The selected details of the experts which include – area of industry, education, work experiences and major responsibilities/area of expertise are shown in Table 5.

**Table 5**

Details of the experts.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Experts | Area of industry | Education | Experience in years | Major responsibilities/area of expertise |
| E1 | Manufacturing | B. Tech and MBA |  > 12  | Adoption of the advanced technologies to perform the manufacturing operations with human–machine collaboration, etc.  |
| E2 | Associate manager in automobile manufacturing  | B. Tech and MBA |  > 15 | Quality management by adopting of the advanced technologies, maintaining value creation for the Industry, etc. |
| E3 | Automobile manufacturing  | B. Tech and MBA |  > 13 | Sustainable manufacturing practices for achieving business objectives and responsible positions in tool engineering, manufacturing, quality engineering, new product development & applications engineering in automobile, etc. |
| E4 | Renewed academician in technology and sustainability  | B. Tech, MBA and Ph.D. | > 18 | His area of working is Industry 4.0, sustainable supply chains, circular economy, cleaner technologies, sustainable societies etc. He did many research projects in these areas.  |
| E5 | Manufacturing | B. Tech and MBA  |  > 15 | He is in a senior position in his industry. He has experienced planning manager with a demonstrated history of working in the automotive industry in the different profiles. Skilled in business planning, demand & supply planning, demand forecasting, and operation excellence. Strong analytical background. Achieving operation excellence through advanced his key area of working nowadays.  |
| E6 | Academic  | B. Tech, MBA and Ph.D. | > 11.5 | His area of working is sustainability, net zero/circular economy, sustainable operations, Industry 5.0, artificial intelligence, etc. He did many research projects in these areas.  |
| E7 | Academic  | B. Tech, M. Tech and Ph.D. | > 8.5 | He is senior research fellow in area of Industry 4.0, circular economy, additive and sustainable manufacturing, lean manufacturing. He is actively involved many research projects related to the adoption of advanced technologies and sustainability, etc.  |
| E8 | Manufacturing | B. Tech and MBA  |  > 15 | He is in a very senior position in his industry. His key responsibilities are sustainable manufacturing practices for achieving business objectives by adopting new and advanced technologies, etc. |
| E9 | Academic  | B. Tech, M. Tech and Ph.D. | > 15 | His area of working is supply chain management, sustainability, circular economy, sustainable operations, operational research, Industry 5.0, artificial intelligence, etc. He did many research projects in these areas.  |

* 1. *Phase 1: Finalization of the criteria and enablers*

Based on the current literature review, five criteria and 15 enablers were identified to implement Industry 5.0. To deal with the vagueness in selection, the PF-Delphi method is employed. Experts from the panel were provided with a survey (questionnaire) to put forward their opinion about the acceptance of the enablers in general. The entries were taken as linguistic terms, later converted to PFNs using the scale in Table 3.

According to the procedure proposed for the PF-Delphi method, expert opinions were obtained in linguistic terms, which were converted to PFNs, then de-fuzzified to obtain the corresponding crisp values. The findings are shown in Table 6. Based on previous studies and consultation with experts, a threshold of 0.6 was decided to determine the selection or rejection of a particular enabler [79]. The experts were also asked for suggestions about the enablers, although they were satisfied with the considered criteria and proposed enablers. The linguistic data were then processed through the proposed PF-Delphi algorithm. All 15 enablers passed the acceptance threshold and hence were accepted.

**Table 6**

Pythagorean fuzzy weights and de-fuzzified values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Enablers  | PF-Weights | Hesitancy  | De-fuzzified value | Selected/Rejected |
| μ | ν | π |
| A1 | 0.7 | 0.4 | 0.35 | 0.6038 | S |
| A2 | 0.7 | 0.4 | 0.35 | 0.6038 | 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 | 0.85 | 0.35 | 0.155 | 0.7880 | S |
| A8 | 0.95 | 0.2 | 0.0575 | 0.9296 | S |
| A9 | 0.85 | 0.35 | 0.155 | 0.7880 | 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 | 0.85 | 0.35 | 0.155 | 0.7880 | S |
| A15 | 0.95 | 0.2 | 0.0575 | 0.9296 | S |

* 1. *Phase 2: Calculation of the criteria weights*

The criteria weights are calculated using the PF-AHP technique. The required hierarchy of selected criteria and enablers is initially developed based on the reviewed literature. The authors then proceed to perform a pair-wise comparison of our selected criteria. For this, a questionnaire was prepared aimed to record the relative importance of each criterion with respect to the other, considering the achievement of our goal of Industry 5.0. This questionnaire was circulated among our panel of experts for their opinions on the relative importance of different selected criteria, in terms of linguistic values, based on the scale given in Table 4.

The data obtained from the above-mentioned survey were then processed through the PF-AHP algorithm. First, the decision matrix mode is taken, and the data are converted into a pair-wise comparison matrix of interval-valued Pythagorean fuzzy numbers (IV-PFN) [70]. Further, the interval multiplicative matrix and determinacy values for the entries in the pair-wise comparison matrix are calculated as shown in Table 7. The final calculated criteria weights are shown in Table 8.

**Table 7**

Pair-wise comparison matrix with IV-PFNs.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|   | C1 | C2 | C3 | C4 | C5 |
| μ(L) | μ(U) | ν(L) | ν(U) | μ(L) | μ(U) | ν(L) | ν(U) | μ(L) | μ(U) | ν(L) | ν(U) | μ(L) | μ(U) | ν(L) | ν(U) | μ(L) | μ(U) | ν(L) | ν(U) |
| C1 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.8 | 0.9 | 0.1 | 0.2 | 0.65 | 0.8 | 0.2 | 0.35 | 0.9 | 1 | 0 | 0 | 0.8 | 0.9 | 0.1 | 0.2 |
| C2 | 0.1 | 0.2 | 0.8 | 0.9 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.8 | 0.9 | 0.1 | 0.2 | 0.65 | 0.8 | 0.2 | 0.35 | 0.65 | 0.8 | 0.2 | 0.35 |
| C3 | 0.2 | 0.35 | 0.65 | 0.8 | 0.1 | 0.2 | 0.8 | 0.9 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.8 | 0.9 | 0.1 | 0.2 | 0.65 | 0.8 | 0.2 | 0.35 |
| C4 | 0 | 0 | 0.9 | 1 | 0.2 | 0.35 | 0.65 | 0.8 | 0.1 | 0.2 | 0.8 | 0.9 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.45 | 0.55 | 0.45 | 0.55 |
| C5 | 0.1 | 0.2 | 0.8 | 0.9 | 0.2 | 0.35 | 0.65 | 0.8 | 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.

|  |  |
| --- | --- |
| C | W |
| C1 | 0.5495 |
| C2 | 0.2257 |
| C3 | 0.1809 |
| C4 | 0.0265 |
| C5 | 0.0281 |

* 1. *Phase 3: Ranking the enablers*

Rankings of the enablers are calculated using the PF-CoCoSo method. The criteria weights calculated in the previous phase using PF-AHP are utilized in PF-CoCoSo. The finalized enablers must have their own relative importance with respect to each selected criterion. Therefore, a questionnaire was prepared and circulated to obtain opinions among our panel of experts. The data were obtained in linguistic terms based on the scale mentioned in Table 3 and then arranged in the form of a decision matrix. By understanding the nature of the selected criteria, they are differentiated as cost criteria (C5) and non-cost or benefit criteria (C1, C2, C3, C4) and further normalized accordingly. The WSM and WPM are then applied, and aggregation strategies are used to obtain a compromise between the two. The values of $k\_{ia}$, $k\_{ib}$, and $k\_{ic}$ are calculated; using those, $k\_{i}$ is calculated for each enabler. The enablers are then ranked based on the decreasing value of $k\_{i}$.

The assessment of $k\_{i}$ values and final rankings of the enablers are shown in Table 9. The enabler bionics (A1) obtained the highest $k\_{i}$ value and, hence, is ranked as 1, followed by IoT-enabled systems (A15), sustainable agricultural production (A2), advanced simulation (A13), and big data (A8) ranked 2, 3, 4, and 5, respectively, followed by other enablers ranked in a similar fashion. Hence, the enabler bionics (A1) has turned out to be the most prioritized enabler, while IoT-based systems (A15) rank second in priority.

**Table 9**

Final ranking of enablers based on assessment of $k\_{i}$ values.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|   | kia | kib | kic | ki | Rank |
| A1 | 0.0819 | 5.7874 | 1.0000 | 3.0694 | 1 |
| A2 | 0.0736 | 4.6652 | 0.8993 | 2.5554 | 3 |
| A3 | 0.0698 | 4.0052 | 0.8527 | 2.2627 | 10 |
| A4 | 0.0595 | 4.1177 | 0.7265 | 2.1970 | 12 |
| A5 | 0.0643 | 3.3947 | 0.7859 | 1.9708 | 14 |
| A6 | 0.0724 | 4.3511 | 0.8841 | 2.4222 | 6 |
| A7 | 0.0634 | 3.6176 | 0.7748 | 2.0476 | 13 |
| A8 | 0.0716 | 4.3727 | 0.8745 | 2.4222 | 5 |
| A9 | 0.0351 | 2.0000 | 0.4293 | 1.1328 | 15 |
| A10 | 0.0632 | 4.2882 | 0.7725 | 2.3019 | 9 |
| A11 | 0.0616 | 4.3988 | 0.7523 | 2.3260 | 8 |
| A12 | 0.0693 | 3.9429 | 0.8465 | 2.2334 | 11 |
| A13 | 0.0642 | 4.7410 | 0.7840 | 2.4833 | 4 |
| A14 | 0.0710 | 4.1553 | 0.8670 | 2.3325 | 7 |
| A15 | 0.0790 | 5.2917 | 0.9645 | 2.8504 | 2 |

* 1. *Sensitivity analysis*

Sensitivity analysis is an effective method to validate a developed framework [80]. It is essential to check the framework's robustness and its behavior in varying circumstances. Researchers have used this technique to validate their models; thus, for the present study, the changes in experts' input are considered while conducting the sensitivity analysis.

The criteria customization (C1) received the highest criteria weight, while human–machine collaboration (C2) received the second-highest criteria weight. This implies that any changes occurring in the weights of these criteria would significantly affect the weights of the remaining criteria. Accordingly, a natural method is to vary their values proportionally. Hence, the criteria weight of A1 (0.5495) is varied from 0.9\*0.5495 to 0.8\*0.5495 until 0.1\*0.5495. After applying these changes, variations were observed in the other criteria weights. The maximum change was observed in criteria bioeconomy (C3), as shown in Table 10. The variations were also observed in the rankings of the enablers, accordingly, as shown in Table 11. The results are shown graphically in Fig. 4.

**Table 10**

Variations observed in criteria weights on performing sensitivity analysis on C1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| C | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
| C1 | 0.5495 | 0.4946 | 0.4396 | 0.3847 | 0.3297 | 0.2748 | 0.2198 | 0.1649 | 0.1099 | 0.0550 |
| C2 | 0.2257 | 0.2532 | 0.2808 | 0.3083 | 0.3358 | 0.3633 | 0.3909 | 0.4184 | 0.4459 | 0.4735 |
| C3 | 0.1809 | 0.2030 | 0.2250 | 0.2471 | 0.2692 | 0.2912 | 0.3133 | 0.3354 | 0.3574 | 0.3795 |
| C4 | 0.0265 | 0.0297 | 0.0330 | 0.0362 | 0.0394 | 0.0427 | 0.0459 | 0.0491 | 0.0524 | 0.0556 |
| C5 | 0.0281 | 0.0315 | 0.0350 | 0.0384 | 0.0418 | 0.0452 | 0.0487 | 0.0521 | 0.0555 | 0.0589 |

**Table 11**

Variations observed in enablers’ ranks on performing sensitivity analysis C1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
| A1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 4 | 4 |
| A2 | 3 | 3 | 5 | 5 | 7 | 7 | 8 | 9 | 9 | 10 |
| A3 | 10 | 10 | 9 | 8 | 8 | 8 | 7 | 7 | 7 | 7 |
| A4 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 |
| A5 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| A6 | 6 | 5 | 4 | 3 | 3 | 3 | 3 | 4 | 3 | 3 |
| A7 | 13 | 13 | 12 | 7 | 6 | 5 | 4 | 2 | 1 | 1 |
| A8 | 5 | 6 | 7 | 11 | 12 | 12 | 12 | 12 | 12 | 13 |
| A9 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| A10 | 9 | 9 | 10 | 12 | 11 | 11 | 11 | 11 | 11 | 11 |
| A11 | 8 | 8 | 8 | 9 | 10 | 10 | 10 | 10 | 10 | 9 |
| A12 | 11 | 11 | 11 | 10 | 9 | 9 | 9 | 8 | 8 | 8 |
| A13 | 4 | 4 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 |
| A14 | 7 | 7 | 6 | 6 | 5 | 6 | 6 | 6 | 6 | 5 |
| A15 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 |



**Fig. 4.** Graphical representation of variations in enablers' ranks for C1 variations.

Similarly, the criteria weight of human–machine collaboration (C2) (0.2257) was varied. The maximum variations are observed in the criteria weight of business and finance administrations (C5). The variations in criteria weights observed are shown in Table 12, followed by variation of enablers' ranks in Table 13. The results are presented graphically in Fig. 5 for these variations as well.

**Table 12**

Variations observed in criteria weights on performing sensitivity analysis on C1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| C | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
| C1 | 0.5495 | 0.5655 | 0.5815 | 0.5976 | 0.6136 | 0.6296 | 0.6456 | 0.6616 | 0.6776 | 0.6937 |
| C2 | 0.2257 | 0.2031 | 0.1806 | 0.1580 | 0.1354 | 0.1129 | 0.0903 | 0.0677 | 0.0451 | 0.0226 |
| C3 | 0.1809 | 0.1862 | 0.1914 | 0.1967 | 0.2020 | 0.2073 | 0.2125 | 0.2178 | 0.2231 | 0.2284 |
| C4 | 0.0265 | 0.0273 | 0.0280 | 0.0288 | 0.0296 | 0.0304 | 0.0311 | 0.0319 | 0.0327 | 0.0335 |
| C5 | 0.0281 | 0.0289 | 0.0297 | 0.0306 | 0.0314 | 0.0322 | 0.0330 | 0.0338 | 0.0347 | 0.0355 |

**Table 13**

Variations observed in enablers’ ranks on performing sensitivity analysis C1.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
| A1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| A2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 |
| A3 | 10 | 10 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 13 |
| A4 | 12 | 12 | 12 | 11 | 11 | 10 | 7 | 7 | 7 | 7 |
| A5 | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 |
| A6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 6 | 6 | 6 |
| A7 | 13 | 13 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| A8 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 3 |
| A9 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| A10 | 9 | 9 | 9 | 9 | 9 | 11 | 11 | 11 | 11 | 10 |
| A11 | 8 | 8 | 8 | 8 | 8 | 8 | 10 | 9 | 9 | 9 |
| A12 | 11 | 11 | 10 | 10 | 10 | 9 | 8 | 8 | 8 | 8 |
| A13 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| A14 | 7 | 7 | 7 | 7 | 7 | 7 | 9 | 10 | 10 | 11 |
| A15 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |



**Fig. 5.** Graphical representation of variations in enablers' ranks for C2 variations.

1. **Results and discussion**

This study shows that customization is the most prioritized criteria for implementing Industry 5.0. From the results of PF-AHP, the criteria customization scored 0.5495, the highest criteria weight of all five criteria. As discovered during the literature review and discussion with experts, the freedom of customization was one of the major states that could not be achieved completely through the methods of Industry 4.0 [9]. The ability to mass-customize and integrate several products is a great advantage to industry and society. It can thus enable extensive personalization of products, much to customer satisfaction. Hence, the level of resilience expected to be imposed becomes much to the desired acceptance. Customization has an indirect but significant impact on other criteria, too. Machines are customized to perform multiple tasks and work alongside humans to present a viable image of the vision of Industry 5.0 [5]. This is also in direct correlation with the objectives of social value creation, sustainability, and bioeconomy, involving collaboration with robots and computers, benefitting humans in many ways. Therefore, customization in every perspective must rightly be the focus.

Human–machine collaboration scored the second-highest criteria weight of 0.2257. It is indeed the next core focus of Industry 5.0, as workable robots and governing software are being developed, integrating AI, IoT [4], and several other features [10]. The development of these collaborative robots and digital assistants will ease human work systems and ensure smooth running of reiterative processes [34]. This would also address sustainability goals number eight (decent work and economic growth) and number nine (industry, innovation, and infrastructure). As stated above, this can be made possible with customization of software and machines for desired applications and achieving resiliency in industry.

Bioeconomy, business and finance administration, and sustainability score third, fourth, and last, respectively. With customization and human–machine collaboration affecting every criterion greatly, these remaining three have their individual influence as well. Bioeconomy integrates two sides, i.e., biology and economy, where biology focuses on the integration of bioproducts, e.g., agriculture [14], animal products, forest and sea products, food products as well as the medicine and surgery aspects, services, and products and, correspondingly, the effect these have on the environment, financial aspects, and business opportunities, hence building a clean, green, resilient, bio-oriented, sustainable economy [29]. Accordingly, business and finance administration come into play [37], where technology is improving transaction methods and even bringing up new assets to invest in. Based on these deductions, it can be observed moving one step with each criterion toward the goal of higher resiliency in industry and sustainability of the environment and social values. The current unsustainable practices in industry will eventually change with these. Adoption of clean energy, reduction of waste, and judicial use of resources will become the industry standard. Humanity will thus progress toward a sustainable and socially active future.

In the same light, the results of PF-CoCoSo give us the priority of enablers that will boost progress in selected criteria toward resiliency in Industry 5.0. Bionics scored the top-most priority, ranking number one. Bionics has a lot of applications in medicine and surgery, including drugs and pharmaceuticals [30]. Taking lessons from the catastrophic damage caused in every industry, in every nation in the world, due to the COVID-19 pandemic, disease prevention through the development of necessary drugs and vaccines has become the top priority. The knowledge and technology must be worked upon and suitably implemented to obtain resilient outputs and social well-being. Other than this, bionic technologies have been developed, such as mechanical replacements for physical disabilities, orthopedic setups, etc. There is, hence, a direct relation of bionics with sustainability goals number three (good health and well-being). Hence, bionics is an essential section of healthcare technologies.

IoT-enabled systems ranked second in priority. Today, it is evident that most services and systems have integrated with the Internet, leading to the birth of IoT. It has been one of the greatest achievements of Industry 4.0 but has yet to fully manifest. With more systems being integrated with IoT, availability of services will become more resilient, and consumers and industry both benefit from this. As a result, a wave of social competence has been initiated. Telecommunication is developing, which has led to better, faster Internet connections [77]. This, with Internet-integrated systems, would mean that services could be available in even remote places. The industry can expand the market for better business, and another step can be taken toward sustainability goal numbers eight and nine. Manufacturing and related industries could have better communication with their upcoming collaborative machines. Thus, it will play a major role for achieving resiliency through system-related automation and availability [4].

Sustainable agricultural production, which has a significant share in the bioeconomy, scored the third rank. Agriculture forms one of the biggest and leading industries, as it directly incorporates the food industry [14]. Also, because agriculture is not possible in every nation, this industry reports high turnovers in countries where it is possible, including the revenue generated from exports. In India, for example, agriculture is a base industry. However, many practices in agriculture, even in advanced nations, are not sustainable and rather cause more harm to the environment in terms of fertility of farmland, groundwater, air quality. Many studies have been conducted in this direction; today, moreover, with the available technology, not only can these practices be replaced with better, sustainable practices, but they allow scientists and farmers to come up with customized methods, which could reverse resulting damages [14]. With collaborative robots finding their work here, too, and availability of clean energy alternatives for farms, agriculture production can be made resilient and sustainable and contribute to conservation of the rural regions and environment in general.

Industry 4.0 introduced and successfully integrated simulation setups for different industries. However, these setups are still not apt, as many real-world aspects are sometimes ignored and thus lack the accuracy when compared with actual, real-world events. Advanced simulation scores the fourth rank in our analysis. Sustainability goal number nine highlights simulation as a needed industry innovation. By advanced, it is focused on shortcomings of the current available simulation techniques as well as software. It also included the mathematics involved in the process of generating a replica for a physical object or any supposed event. The techniques are powerful but still possess a great scope of development, especially in manufacturing and thermal industries, where many factors are involved in the production, and some are often ignored when developing a model, generally because of an inability to process those. Advance simulation will employ better and more effective techniques to consider and process those factors as well, thus improving production quality and application manifolds, along with current levels of resiliency.

Big data, which ranked fifth in our analysis, is another byproduct of Industry 4.0. The huge amount of data collected has thus far enhanced and personalized user experience. However, other than this, it has had not many significant applications being applied. In current developments of Industry 5.0, big data offers more application opportunities, especially in social grounds. It can be the feed data for AI systems, which will significantly enhance the performance, resiliency, and service of these systems [7]. Data from industries can be utilized in simulation practices and in autonomous systems for better performance and enhancing the production process in industries such as manufacturing. Big data holds the secrets of customer needs and desires and can thus be applied to provide the most comfortable, essential, and practically required services.

1. **Implications and proposed research propositions**

This study proposes theoretical as well as practical implications. Some major themes are proposed in this study that could be adopted to enhance resiliency in industry while retaining social values.

**Proposition 1.** Products must be customized to meet customer desires by personalizing options according to individual needs.

Personalization is in great demand among customers [9]. It will appeal to the needs of each customer, as they will have a variety of options to customize their products according to their requirements and liking. Hyper-customization is a personalized marketing strategy that applies cutting-edge technologies such as AI, ML, cognitive systems, and computer vision to real-time data to provide a more specific product to the targeted customer [81]. Better customer satisfaction would mean an improved social atmosphere, which ensures the uniqueness of each product [5].

**Proposition 2.** Services must be customized to ensure greater availability, accessibility, and improved quality.

From Internet-based services to service stores and even aftersales services, enterprises need to incorporate technologies to ensure smooth and satisfactory customer service [82]. Availability of multiple services on a single platform appeals to the targeted consumer; however, integrating two or more services would ease their accessibility, reduce time, and ensure faster performance [7]. Tao et al. [83] presented how cloud manufacturing can be deployed as a service-oriented manufacturing model constituting cloud computing, IoT, virtualization and service-oriented technologies, and advanced computing technologies. It aims to realize the full sharing and circulation, high utilization, and on-demand use of various manufacturing resources and capabilities by providing safe and reliable, high-quality, cheap, and on-demand used manufacturing services for the whole life-cycle of manufacturing.

**Proposition 3.** Customize the work environment with robots performing automatable tasks and redundant jobs.

A huge workforce is often employed in factories and other industries to perform re-iterative tasks, which could be efficiently performed by robots and automated machines [32]. Often, this workforce has skilled workers and educated persons [84,85]. This human caliber can be employed elsewhere to perform better tasks, which are not repetitive and ensure a better social environment for workers [17]. An example case study is presented, i.e., Bundesgartenschau 2019, a wooden pavilion with a robot hand developed by the joint venture of Mullerblaustein Holzbauwerke, KUKA, and Institute for Computational Design and Construction for timber construction. This wooden pavilion consists of 400 elements, all crafted by robots, which perform all the carpenter tasks such as bisecting wooden beams, moving large components, assembling, and applying adhesives, thus enabling the robotics and craftsmanship to form a collaboration [81,86].

**Proposition 4.** Customize the work environment with IoT and AI-based systems.

AI systems can efficiently perform many tasks and services, which can be trained to handle customers, resolve queries, assist, and provide solutions in general work situations. These systems will perform mostly re-iterative tasks quickly, thus reducing human errors and the extra time taken that could slow the service process [87]. Thus, these efforts will ensure resilient service and a better social environment for the customer [8,57]. The disruptive technologies that enable Industry 5.0 like DT, robots, 5G and beyond, ML, IoT, EC, etc., aligned with the smartness and innovation of humans [21], can help industries in meeting demand and delivering personalized and customized products at a faster pace. This helps supply chain management (SCM) integrate mass customization, a key concept in Industry 5.0, into their production systems [40,81].

**Proposition 5.** Engaging in extensive human-machine collaborative strategies in the industry will ensure high accuracy in predictions and implementations.

Utilizing high accuracy of machine computations monitored and processed collaboratively with human intelligence will provide organic elements within the sought-after computational results [88]. Industries like manufacturing will benefit the most, as computational and simulation data will include human synergy [17]. The human-robot collaborative (HRC) manufacturing executes the assembly of components in a manufacturing division in collaboration with a robot and human. The integration of machine–human cognition is modeled and applied for this collaboration work in real-time. The fifth industrial revolution maintained the merits of the fourth industrial revolution and brings back human labor for production. The fifth revolution facilitates robots and skilled labor to work together in order to produce customized products and services in Industry 5.0 [89].

**Proposition 6.** Adopting bionics will significantly boost medicine, surgery, and other aspects of the healthcare industry.

With exoskeleton technology, bionic technologies have great potential for applications in industries like mining, excavation, and the military [15]. Bionic aids have been useful in assisting the disabled [13]. Other than these, the outbreak of COVID-19 has put forward an urgent need to increase research of improved pharmaceuticals, along with suitable and effective vaccines. This also calls for Adopting a resilient green supply chain providing a boost to the pharmaceutical industry with the inclusion of green methods, that is, a step toward sustainability [27]. Smart wearable devices such as the Apple Watch, Fitbit, etc., with several health and fitness apps installed, recently have become popular [90]; these provide a digital assistant while exercising and monitor health status, such as heart rate in real-time. Apple Watches were reported to have saved lives by notifying wearers of cardiac malfunctions observed by its electrocardiogram (ECG) feature. Thus, Adoption of these bionics, technologies, and methods will be a strong step toward a resilient healthcare.

**Proposition 7.** Adopting the proposed enablers in industry and investing more in industries promoting bioeconomy will ensure the progress of humanity toward achieving a sustainable future.

Unthoughtful actions of human beings have led to severe degradation of the environment and natural resources; thus, it has become urgent that sustainable practices must be adopted everywhere. There must be wise use of resources, reducing waste generation, reusing, and recycling products to the best [68,69]. The bioeconomic industries must be integrated with suitable technologies, and the methods of Industry 5.0 must be adopted to promote sustainable production and the preservation of the environment [1,41]. Industry 5.0 is a concept designed to harmonize humans and machines' working space and efficiency consistently. Enabled by various emerging applications and supporting technologies, the proposed Industry 5.0 enablers are expected to increase manufacturing production and customer satisfaction [81].

1. **Conclusion**

Industry 5.0 is focused on delivering life-enhancing products/services to society. However, many aspects were either not considered nor reached in Industry 4.0, such as mass personalization, coworking robots and AI systems, sustainable practices, and bioeconomy. Now it is peak time, with alarming disturbances happening in nature due to negligent human activities; such practices must change, and sustainable, more resilient alternatives must be adopted into our industries as well as day-to-day lives. Today, the knowledge and technology are available to implement better practices; hence, these must work to integrate those and preserve our society and our planet. Major highlights have been the interrelationships of the selected criteria, and how customization must be addressed in parallel with other criteria. Selected enablers are important, where healthcare and medicine are being targeted through the bionics portal. Agriculture and related industry promote bioeconomy extensively; hence, more investment of both financial and technological nature would help the world progress toward building a bioeconomy. IoT-enabled systems, AI-based management systems, advanced simulation, and renewable energy find their application in most of the existing sectors and should be implemented on a massive scale. Thus, more resiliency can be achieved in the industry, and focus could be placed on human social aspects and social value creation as well. The end goal is to achieve a bio-oriented, sustainable society, thus preserving the values of humanity and the environment. This is the complete idea of Industry 5.0.

Although Industry 5.0 has these positive visions, there are some issues regarding the impact of robots in the industrial sector will have. There could arise legal and regulatory issues since there are no laws that address the use of Personal Assistant Robots (PAR), or the type of robots to be used in workplaces [5]. The psychological issues would be related to both the workers and consumers of robotic services as they either might feel uncomfortable, stressed being strictly supervised under a machine, or could develop an addictive dependency on the robots [32]. Clear communication between the robots and the worker/consumer is necessary not to misunderstand instructions. There are also concerns of job-related issues, such as whether the entry of robots leads to a loss of jobs. Adding robots into this competition could also complicate management and organizational behavior [5].

With the present study, the authors have covered most of the key execution points of the objective, considered the most credible papers, and identified the most impactful criteria and enablers. It is recommended to use the experts' knowledge to broaden the criteria and identify more enablers for Industry 5.0. As the concept of criteria is subjective, and there could be inherent uncertainty in experts' judgment, PFS was used to capture this vagueness. It is recommended to use IV-PFN in the calculation frameworks to record and process maximum uncertainties and produce better results. The proposed framework of PF-Delphi and PF-AHP-CoCoSo has produced effective results. However, it still has limitations and can be accepted as an open door for researchers. Any biasing in judging the relative importance of the criteria and enablers could lead to ambiguous results. Hence, the experts' panel must produce an unbiased rating in the questionnaire.

Despite certain limitations, the study has put forward a scope for future research. The method of PF-Delphi, incorporating PFS into the classical Delphi technique, is proposed for the first time in this study. It is apt for producing correct results and can be utilized by researchers in their studies. It might also have shortcomings, which are welcomed to be addressed in future works. The resulted ranking of enablers provides a basic priority list, which can be to referred by industrialists for their investments, to proceed toward a resilient and socially sustained Industry 5.0. Researchers can further work on the selected criteria and expand the horizon, thus making way for better investment strategies. Therefore, this study can be referenced for understanding the MCDM techniques utilized, criteria selected, or finalized enablers. It will thus give a clear idea about the objectives of Industry 5.0.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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