**Graphical Abstract**

Applying Fuzzy Evaluation Method to assess the enabler’s readiness scores in case studies

Extracting relevant Industry 4.0 enablers in CP and CE within ethical context

Validating the enablers by Fuzzy Delphi

Determining the importance of enablers by IVFS AHP method

Determining the enabler’s priority

Calculation of enabler’s readiness score

Recognizing and validating Industry 4.0 enablers

Meticulous literature review

**Research Highlights**

* Conducted an extensive literature review to extract a broad range of Industry 4.0 enablers and validated.
* Determining the preference and importance of enablers and sub-enablers by applying Interval-Valued Fuzzy Sets based Analytical Hierarchy Process.
* Fuzzy Evaluation Method was used to obtain the readiness score of Industry 4.0 enablers.
* Proposed a novel framework for assessing Industry 4.0 enablers in Cleaner Production and Circular Economy implementation in the context of ethical business development.

**Industry 4.0 Enablers for a Cleaner Production and Circular Economy within the context of Business Ethics: A Study in a Developing Country**

**Abstract**

To achieve sustainability, businesses are adopting Cleaner Production (CP) and Circular Economy (CE) practices for producing better quality products at the lowest cost while decreasing the negative environmental impact of their operations. The implementation of these practices is highly influenced by Industry 4.0 technology’s enablers, particularly within the context of ethical and sustainable business development. In this paper, a novel framework is proposed to assess the importance of Industry 4.0 enablers for implementing CP practices embedded in CE in the context of ethical societies and assess an industry’s readiness. Firstly, the most effective context-related Industry 4.0 enablers are extracted from previous studies and validated through a Fuzzy Delphi method. Secondly, the Interval-Valued Fuzzy Sets (IVFS) based Analytical Hierarchy Process (AHP) method is applied to evaluate the enablers’ weight. Due to existing ambiguities in the enablers, IVFS was applied to model the uncertainty in an interval [0,1]. The final results indicate that the most important enablers are “Technical Capability”, “Security and Safety”, Policy and Regulation”, “System Flexibility”, “Education and Participation” and “Support and Maintenance” respectively. Thirdly, the Fuzzy Evaluation Method (FEM) was followed to evaluate the readiness score of Industry 4.0 enablers for implementing CP practices embedded in CE and evolving ethical principles of corporate social responsibility. This paper contributes to the CP, CE and ethics body of knowledge by proposing a framework for assessing wider dimensions of Industry 4.0 enablers during the implementation of CP and CE practices and providing ethical and sustainable business development.

***Keyword:*** Industry 4.0, Cleaner Production, Circular Economy, Business ethics, AHP, Fuzzy Sets Theory, Fuzzy Evaluation Method

**1. Introduction**

Strong competition in business causes organizations to change manufacturing procedures and production patterns as well as making large transformations in resource performance (Rosa et al., 2020). One of the best ways to optimize the usage of resources is by deploying Cleaner Production (CP) and Circular Economy (CE) practices within a company’s operations. Circular Economy (CE) concentrates on the regeneration and restoration of products and components (Devi et al., 2020; Rosa et al., 2020). CE tries to prevent businesses from using toxic materials to facilitate the reusing of the products. This contributes to enhancing resource efficiency and environmental performance. CE is also considered as an option for replacing the traditional linear model by creating value-added aimed at the long-lasting use of manufactures and components (Devi et al., 20020; Rosa et al., 2020). CP is seen as a prerequisite implementation of CE. The implementation of CE depends on the adoption of CP. For instance, pollution and waste prevention are the main responsibilities of CE, and these can only take place through the adoption of CP (Sousa-Zomer et al., 2018). With the arrival of Industry 4.0, many businesses have faced big transformations and changes in terms of organizational procedures and business operations. Industry 4.0 creates more flexible and efficient processes to manufacture better quality products at a minimum cost as well as improving a company’s competitive advantage (Devi et al., 2020). Industry 4.0 is a strong enabler which has a constructive effect on different business functions. Industry 4.0 optimizes the use of computers and robots by making remote connections to decreasing human interactions and activities. Industry 4.0 is an essential requirement for leveraging the value chains of businesses (Singh et al., 2019). Technologies such as the Internet of Things (IoT), Big Data, Artificial Intelligence (AI) and Cloud Computing help to improve high-quality product manufacturing at a minim cost. Industry 4.0 can change all business processes including designing, production and delivery aimed at leveraging the efficiency of manufacturing (Rajput and Singh, 2019).

Different studies have shown that Industry 4.0 can work as an enabler for CE (Aranda-Uson et al., 2020; Devi et al., 2020; Rosa et al., 2020). Businesses cannot prevent themselves from applying Industry 4.0 systems. The basic contribution of Industry 4.0 is digitalizing CE practices through different cutting-edge technologies. Industry 4.0 creates numerous opportunities for businesses to improve circular performance and evolving ethical principles of corporates social responsibility (CSR). Industry 4.0 can act as a strong enabler for optimizing the usage and utilization of resources as well as improving the monitoring of product lifecycle steps (Rosa et al., 2020).

One of the main objectives of CP and CE initiatives is to achieve sustainability in the management of supply chains. In this context, the application of Industry 4.0 as an enabler for CE does not necessarily ensure sustainable supply chains if standard business ethics are not followed. Therefore, these standards should also be considered through supply chain activities to achieve sustainability (Mirghafoori et al., 2018; Baliga et al., 2019). Business Ethics is delineated as moral concerns in circumstances, behaviours and actions of main suppliers through the entire supply chain (Goodpaster, 1991). Business Ethics principles are seen as one of the main pillars of the management of contemporary supply chains, which have to be observed to reach long-term sustainable goals (Baliga et al., 2019; Mirghafoori et al., 2018; Yun et a., 2019).

Different studies have been conducted to explore how Industry 4.0 can work as an enabler for the implementation and improvement of CE (Aranda-Uson et al., 2020; Rosa et al., 2020). Following a meticulous literature review, some important research questions were formulated:

*RQ1*. What is the main and broad comprehensive set of Industry 4.0 enablers that could facilitate and support the implementation of Cleaner Production (CP) embedded with Circular Economy (CE) practices following business ethics?

*RQ2*. What is the importance of Industry 4.0 enablers in the sustainable implementation of CE and CP in the context of business ethics?

*RQ3*. What is the best method for modelling the inherent existed uncertainty in some of the enablers and sub-enablers to achieve a more meticulous computation?

Following these research questions, the main paper’s objectives are:

* To recognize the broad comprehensive set of enablers for implementing CP practices embedded with CE in the context of an ethical society.
* To find the preference and importance of Industry 4.0 enablers in implementing and developing these practices and evolving ethical business principles and sustainable business performance.
* To find an effective method for modelling the subjective concept of Industry 4.0 enablers in the implementation of CP and CE and ethical and social performances.

The present work is organized into eight sections. The introduction is provided in the first section. In the second section, the most relevant studies related to Industry 4.0 in association with CP, CE and ethical and social performance were reviewed and the most impactful enablers identified. The identification of research gaps and problem definition are included in section three. In the fourth section, the research methodology is introduced. In section 5, the extracted enablers are validated through Fuzzy Delphi and categorized by expert’s judgments, then such enablers and sub-enablers are assigned weights by using the IVFS AHP method. Then, a framework is developed and a case study conducted to validate it. In section six, the analysis and discussion are provided. The theoretical and practical implications are included in section seven, whereas the last section presents the conclusion of the research.

**2. Literature review**

In this section, the most relevant studies of Industry 4.0 in association with CP and CE implementation are reviewed and the most effective Industry 4.0 enablers identified. Different studies have displayed the game-changing role of Industry 4.0 in enabling and enhancing the performance of CP and CE in various contexts (Aranda-Uson et al., 2020; Devi et al., 2020; Rosa et al., 2020). Lu et al. (2020) conducted a research study to examine the important role of Carroll’s pyramid model in small-medium enterprises (SMEs). The outcome suggested that the inclusion of Industry 4.0, CP and CE creates a synergetic business opportunity that results in sustainable development by enhancing environmental management, production efficiency and sustainable development for SMEs in the context of ethical sustainable development. Ma et al. (2020) proposed a data-driven based sustainable framework. The paper exhibited that Industry 4.0 technologies, e.g. Big Data and IoT, create numerous opportunities for a fast and efficient implementation of CP by making energy-efficient decisions for energy-intensive manufacturing enterprises. Pham et al. (2019) proposed a framework for explaining the effect of Industry 4.0 in accelerating CE. The framework was developed for the electric scooter industry. The framework is comprised of enablers that include IoT, Big Data, Cloud Computing, Data-driven Analysis, Cyber-Physical System, Smart Feature (smart sensors, wireless communication) and Safety and Environment.

Rajput and Singh (2019) identified the most important Industry 4.0 enablers for improving CE and manufacturing performance. These enablers included Scalability, Modularity, Reliability, Quality of Services, Integration, Self-organization, Maintenance and Recovery, Flexibility, Visual Computing, IoT, Self-Configuration, Value Networks, Block Chain, Infrastructural Building, Service Economy, System Integration, Energy and Waste Recovery, Big Data and Collaborative Robotics. The study applied the DEMATEL method to recognize the cause and effect of Industry 4.0 enablers and CE for leveraging the effectivity of manufacturing performance. [Nascimento](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=57195542948&amp;eid=2-s2.0-85057315102) et al. (2019) proposed a business model for integrating Industry 4.0 with CE to reuse and recycle wasted material. The business model considered two Industry 4.0 enablers, i.e. Smart Production System and Additive Manufacturing, as the main factors having a profound effect on the improvement of supply chain and CE. A qualitative statistical method was applied to determine the association between the enablers in the context of CE. [Chauhan](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=57204944385&amp;eid=2-s2.0-85068738105) et al. (2019) suggested a framework for integrating Industry 4.0 and CE. The study showed that management involvement and commitment are critical factors to integrate these two concepts. Moreover, IoT and Cyber-Physical Systems were the main technological enablers for enhancing CE in different contexts. Qualitative and statistical methods were applied to assess the potential association between enablers. [Lopes](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=54977014200&amp;eid=2-s2.0-85045041008) et al. (2018) carried out a research study to explore whether Industry 4.0 could enhance the performance of CE and manufacturing sustainability. Their research mostly concentrated on investigating different Industry 4.0 enablers in the implementation and development of CE. Lopes et al. (2018) considered enablers that included IoT, Cloud Computing, Additive Manufacturing and Cyber-Physical Systems.

Each of the aforementioned studies focused on limited aspects of Industry 4.0 enablers in enhancing and digitalizing manufacturing processes and CE. These studies thus suffer from the lack of a framework for considering a broad view of Industry 4.0 enablers that can have a direct impact on leveraging production processes, supply chains and CE. Based on the reviewed studies and experts’ comments, the most effective enablers were identified in order to unveil a comprehensive set affecting CE, supply chain management and ethical sustainable performance. Table 1 shows the Industry 4.0 enablers for CP and CE implementation in the context of business ethics.

**Table 1.** The most effective industry 4.0 enablers for improvement of CP and CE implementation within context of business ethics.

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Industry 4.0 enablers** | **Description** | **References** |
| 1 | Training Employers for better use of Industry 4.0 technologies in the context of business ethics | Raising employers’ awareness by training them in different aspects of Industry 4.0 for evolving ethical principles of corporate social responsibility. Such practices help to increase Personal Staff Value (PSV) for behaving ethically in a business environment as well as considering social responsibility for sustainability in SCM. | Seuring et al. (2019); Moktadir et al. (2018); Yun et al. (2019) |
| 2 | Assuring the security of Industry 4.0 systems | Boosting up employer’s confidence about the security of Industry 4.0 is conducive of a fast implementation of CP and CE, which is seen as a policy maker’s social responsibility. Thus, trust and commitment will be leveraged through suppliers as the main pillar of CSR. This is likely to increase sustainability through the entire supply chain | Liu et al. (2017); Machado et al. (2020); Lu (2017); Gonzalez-Trejo et al. (2013) |
| 3 | Applying Machine learning systems | Machine learning is considered an artificial intelligence tool for enhancing production efficiency and product and service design | Gmelin and Seuring (2014); Katiyar et al. (2018); Hong et al. (2019) |
| 4 | Applying flexible Industry 4.0 systems | A flexible industry 4.0 system accelerates its integration with CP and CE, creating a large number of opportunities | Xu et al. (2016); Gmelin and  Seuring (2014) |
| 5 | Effective performance metrics for assessing the effectivity of CP and CE embedded with Industry 4.0 | Applying sustainable and robust metrics is required to monitor the progress of CP and CE implementation integrated with Industry 4.0. Moreover, business ethics criteria should be considered as social metrics for assuring sustainability in SCM | Lu (2017); Sahebi et al. (2017); Alexander et al. (2014) |
| 6 | Applying effective optimisation techniques | Optimisation techniques are seen as Artificial Intelligence tools to standardize and optimize CP and CE implementation processes for sustainable development | Mangla et al. (2013); Rajak and Vinodh (2015) |
| 7 | Using Industry 4.0 systems for assessing regular tracking of stock and in-process inventory | Industry 4.0 paves the way for more efficient product design as well as better in-process inventory monitoring | Schwab et al. (2019); Seuring et al. (2019) |
| 8 | Applying man-machine interaction | High interactions between machine and human improve production efficiency and sustainable CP and CE implementation and development | Lu (2017); Sahebi et al. (2017) |
| 9 | Applying Industry 4.0 supportive policies | Supportive policies have a direct effect on the further development of a sustainable environment and further enhancement of CE and CP. Such a policy can help evolve ethical principles of social responsibility and increasing policy maker’s responsibility for a more sustainable society | Schwab et al. (2019); Hong et al. (2019) |
| 10 | Applying Internet of Things | Applying IoT helps organizations to get a competitive advantage for better process monitoring as well as providing smart supply chain for production efficiency. It also has a direct influence on the effectivity and sustainability of CE and CP | Moktadir et al. (2018); Hong et al. (2019) |
| 11 | Allocating appropriate budget for fostering Industry 4.0 | Designating an appropriate budget for the development of smart Industry 4.0 facilitates accelerates the sustainable performance of CP and CE | Stoycheva et al. (2018); Latif et al. (2017) |
| 12 | Applying smart factory equipment | Using smart factory components ensure overall sustainable development, including environmental, economical and social | Liu et al. (2017); Beekaroo et al. (2019) |
| 13 | Management level participation in developing industry 4.0 | Management commitment and support is a key business strategy to develop Industry 4.0 for more sustainable development of CP and CE within the context of business ethics. Additionally, management support paves the way for creating ethical behaviour and more commitment between suppliers to obtain a more effective SCM | Schwab et al. (2019); Seuring et al. (2018); Kumar et al. (2020) |
| 14 | Granting reward and incentives policy for faster development of Industry 4.0 | Reward policies help employers to get more involved in adopting Industry 4.0 for sustainable implementation of CE and CP and boosting up the ethical principles of corporate social responsibility | Mani et al. (2018); Liu et al. (2017); Latan et al. (2020); Latan et al. (2019a) |
| 15 | Ensuring employer’s privacy by deploying secure industry 4.0 | Keeping an employer’s privacy is one of the main aspects of business ethics principles. Such an issue can take place through creating a secure Industry 4.0 platform to reach more sustainable SCM. | Xu et al. (2016); Gmelin and  Seuring (2014); Mirghafoori et al. (2018) |
| 16 | Recognizing potential implications of Industry 4.0 | It is important to make employers aware of the precise implications and results of Industry 4.0 applications in the further development of CE and CP sustainability | Liu et al. (2017); Beekaroo et al. (2019) |
| 17 | Creating a smart supply chain through Industry 4.0 | The utilization of Industry 4.0 in supply chains increases the efficiency and performance of manufacturing processes and effectivity of CP and CE implementation | Ma et al. (2020); Lu (2017); Sahebi et al. (2017) |
| 18 | Constant tracking of suppliers through Industry 4.0 systems | Smart systems help stock managers to make the right decision for keeping the stock at the optimum level for a sustainable business operation | Moktadir et al. (2018) |
| 19 | Knowledge-based decision making in supply chain | Knowledge-based decision increases the quality of sustainable development of CE and CP and improves operational efficiency. Such logical decision paves the way for observing business ethics principles aimed at reaching more sustainable SCM. | Stoycheva et al. (2018); Latif et al. (2017); Yun et al. (2019); Latan et al. (2019b) |
| 20 | Applying Big Data | Analysing a large amount of collected data helps to make wiser and more precise decisions and have a better understanding of all situations to create a sustainable business development | Pham et al. (2019); Devi et al. (2020) |
| 21 | Visual computing | Computing tools help business managers to have a better analysis of supply chains and operational management  of CP and CE implementation | Devi et al. (2020) |
| 22 | Additive manufacturing | It is a strong tool which can replace conventional methods and paves the way for further customization in the sustainable development of Industry 4.0 integrated with CP and CE implementation | Devi et al. (2020); [Nascimento](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=57195542948&amp;eid=2-s2.0-85057315102) et al. (2019) |
| 23 | Operational efficiency | Industry 4.0 provides a great opportunity for dealing with complexity and improving manufacturing efficiency and business sustainability in CP and CE implementation. Applying business ethics principles have a direct effect on operational efficiency in sustainable SCM. | Lu et al. (2020); Devi et al. (2020); Tortorella et al. (2018); Gonzalez-Trejo et al. (2013) |
| 24 | Cloud computing | It provides a high volume of data collection and wide sharing of information between different sectors to make a more ethical business environment. Cloud computing plays an important role in fostering business ethics principles by providing higher transparency in data distribution. | Devi et al. (2020); [Lopes](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=54977014200&amp;eid=2-s2.0-85045041008) et al. (2018); de Bruin and Floridi (2017) |
| 25 | Integration of Industrial systems | It facilitates a smoother exchange of resources and lets them be shared efficiently between different sectors aimed at enhancing the efficiency of production performance | Devi et al. (2020); [Nascimento](https://bbibliograficas.ucc.edu.co:2153/authid/detail.uri?authorId=57195542948&amp;eid=2-s2.0-85057315102) et al. (2019); Rajput and Singh (2019) |
| 26 | Infrastructure building | To apply smart equipment, it is highly required to prepare the needed infrastructure to embed the new equipment that leads to a more sustainable CP and CE implementation | Kalmykova et al. (2018); Rajput and Singh (2019) |
| 27 | Applying Block chain | It is considered as a strong Industry 4.0 tool for regulating financial transactions and providing agile and flexible CE | Rajput and Singh (2019); Queiroz and Wamba (2019) |
| 28 | Self-adaptability | It is highly required to make the CP and CE implementation process integrating with Industry 4.0 technologies to reach more sustainable manufacturing performance | Athreya and Tague (2013); Rajput and Singh (2019) |
| 29 | Safety | Employer’s safety is so pivotal and critical aspect in CP and CE implementation. Such an issue can be empowered through integration with Industry 4.0 capabilities. Thus, a safe environment encourages entities to behave more ethically and morally within a safe environment which increases sustainability in SCM. | Pham et al. (2019); Baliga et al. (2019) |

As it was explained in this section, each study has considered restricted aspects of Industry 4.0 enablers for implementing CP and CE. Moreover, each study mostly tried to use statistical methods to recognize the association of enablers with the concept of CE. In the next section, the literature review research gaps and problem definitions are discussed.

**2.1. Research gap and problem definition**

Industry 4.0 is a strong strategic tool for enhancing the efficiency and performance of supply chains and circular economy. A limited number of researches have been carried out to investigate and explore Industry 4.0 enablers (Aranda-Uson et al, 2020; Rosa et al., 2020). As discussed in Section 2, there are five critical research gaps identified from the previous studies:

* Each study has considered limited aspects of Industry 4.0 enablers and they have not proposed a comprehensive set of enablers to create boarder and wider aspects of such phenomenon in supply chains, CE and sustainable ethical business development (Nascimento et al., 2019; Pham et al., 2019; Rajput and Singh, 2019).
* The most commonly used methodology employed in the reviewed studies was statistical methods which were trying to prove any potential association between industry 4.0 enablers and CE (Devi et al., 2019; Nascimento et al., 2019). Since some of the enablers, e.g. education, management support and commitment, are subjective concepts and inundated with high ambiguity, statistical methods are unable to recognize the appropriate and precise association and capture that inherent ambiguity.
* The previous studies mostly concentrated on the exploration of Industry 4.0 enablers and their effects on CE and supply chains for more sustainable and effective performance (Rajput and Singh, 2019; Singh et al, 2019). No studies have developed a framework to denote the importance and priority of such enablers to help business managers adapting their potential plan with enabler’s preference.
* No studies have been conducted so far to propose a framework for evaluating the readiness score of Industry 4.0 enablers in CE in the context of an ethical society and social responsibility as well as supply chains.
* Previous studies have focused on specific country and territory in order to apply the suggested framework (Devi et al, 2020; Singh et al, 2019) but no studies have been carried out within the context of Iranian manufacturing performance.

In this research, a novel framework is proposed for assessing Industry 4.0 enablers in terms of supply chain and CE implementation and evolving ethical principles of social responsibility. The framework manages to fill the recognized existed research gaps in the previous studies by considering wider Industry 4.0 enablers and applying an appropriate soft computing method.

**3. Research Methodology**

In this section, the applied research methodology is explained. Due to the existing ambiguity in some of the enablers and sub-enablers, Fuzzy sets theory was applied to capture the vagueness of the data. Similarly, due to the absence of experts’ agreement on setting a single membership function for triangular numbers, Interval-Valued Fuzzy Sets (IVFS) was applied to model the experts’ judgments in an interval.

Owing to the presence of various enablers and sub-enablers in the research problem, Multi-Criteria Decision Making (MCDM) methods were used to determine their importance. Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP) are the two most common MCDM-based methods for assigning weight and determining the criteria (enablers) preferences. The absence of a correlation and dependency between criteria and sub-criteria (sub-enablers) called for applying AHP rather than ANP. Firstly, Fuzzy sets theory and Interval-valued fuzzy sets theory were employed to model the existing uncertainty in the problem. Secondly, Fuzzy Delphi method was used for validating the enablers through expert judgment. In the next section, the IVFS AHP method is presented and used to assign weights to the Industry 4.0 enablers. Finally, the Fuzzy Evaluation Method (FEM) was introduced for calculating the readiness score of Industry 4.0 enablers in any potential case study.

The research methodology followed in this paper makes three important contributions in the context of CP, CE and Industry 4.0.

* No previous studies have applied Interval-Valued Fuzzy Sets (IVFS) to capture experts’ judgment and model an interval in the context of CP, CE and Industry 4.0;
* Fuzzy Evaluation Method (FEM) has been integrated with IVFS AHP to conduct a quantitative analysis;

**3.1. Interval-valued Fuzzy Sets Theory**

Fuzzy sets theory was firstly proposed by Zadeh in 1965 for modelling existed uncertainty in real phenomena (Tabaraee et al., 2018). A fuzzy set in a universe discourse of is delineated by a membership function that is associated with a member in . Membership function takes a value between zero and one. A higher value of membership function shows higher members belonging to fuzzy set (Chu and Nguyen, 2019).

Fuzzy numbers are a subset of real numbers. Triangular fuzzy numbers are the most common fuzzy numbers. These are made of lower band , median band and upper band . The membership function of triangular fuzzy numbers is delineated by (Chu and Nguyen, 2019):

(1)

Since experts are unable to convey their judgments by a number between zero to one, they express their opinions in an interval [0,1]. Additionally, experts do not have agreement on allocating a single membership function, therefore, normal fuzzy numbers are defined in an interval. Interval-valued fuzzy theory was proposed by Gorzlczany and Turksen in 1987 to model a problem’s uncertainty in an interval (Wang et al., 2018).

**3.1.1. Mathematical Preliminaries**

The most basic concepts of interval-valued fuzzy sets are explained as (Wang et al., 2019):

**Definition 1.** AFuzzy set is delineated on given by:

(2)

(3)

(4)

Where and denote the lower and upper limits of membership degree, therefore, the membership degree of each member is delineated by . The maximum and minimum membership value of is denoted by and .

**Definition 2.** Interval-valued triangular fuzzy number is shown by:

(5)

Where and show lower and upper components of . Each component is comprised of the left boundary, median boundary and right boundary, which are represented by ، and respectively. The maximum value of the membership function is denoted by .

**Lemma 1.** If (where ), Interval-valued triangular fuzzy numbers are converted into normal triangular fuzzy numbers.

**Lemma 2.** If , the triangular fuzzy numbers are changed to crisp numbers.

In this research, Interval-valued triangular fuzzy numbers were applied to model the existing uncertainty.

**Definition 3.** The most practical arithmetic operations on two interval-valued triangular fuzzy numbers and are as:

**Table 2.** Arithmetic operations

|  |  |  |
| --- | --- | --- |
| **No.** | **Operation type** | **Result** |
| 1 | Addition |  |
| 2 | Subtraction |  |
| 3 | Multiplication |  |
| 4 | Multiplication of a positive crisp number (k) into interval-valued triangular fuzzy number |  |
| 5 | Multiplication of a negative crisp number (k) into interval-valued triangular fuzzy number |  |

**3.2. Fuzzy Delphi**

The Delphi method was proposed by Dalkey in order to validate experts’ judgments and opinions. In this method, a questionnaire is developed and distributed among a handful of experts to conduct group decision-making examinations (Noori et al., 2020). Since some of the information is associated with subjective concepts, it is highly recommended to use fuzzy numbers rather than crisp and definite numbers. The Fuzzy Delphi method was proposed by Kaufmann and Gupta in 1988. In the present research, Fuzzy Delphi was used to verify the identified Industry 4.0 enablers presented in Table 2. A Fuzzy Delphi study is conducted through the following steps (Singh and Sarkar, 2020; Zhang and Lam, 2019):

**Step 1. Extracting Enablers:** In the first step, the most effective Industry 4.0 enablers were identified from relevant studies. These are shown in Table 1.

**Step 2. Collecting experts’ judgments:** Experts’ judgments were collected through a questionnaire handed out to a handful of experts to provide their opinions by selecting a linguistic variable, see Table 3.

**Table 3.** Converting linguistic variables into fuzzy numbers

|  |  |
| --- | --- |
| **Linguistic Variables** | **Fuzzy triangular fuzzy number** |
| Extremely unimportant | (0.1,0.1,0.3) |
| Unimportant | (0.1,0.3,0.5) |
| Normal | (0.3,0.5,0.7) |
| Important | (0.5,0.7,0.9) |
| Extremely important | (0.7,0.9,0.9) |

**Step 3. Converting the linguistic variable:** After collecting the experts’ judgments, they were turned into fuzzy numbers following Table 3.

(6)

Where shows th enabler’s importance of th expert. shows the number of enablers and denotes the number of experts.

**Step 4. Data Aggregation:** In this step, experts’ judgments were aggregated to determine the fuzzy weight of th enabler by:

(7)

**Step 5. Deffuzification:** In the last step, the fuzzy triangular number was deffuzified by:

(8)

The computed value was then compared to a threshold . If the score exceeded the threshold it was then considered as an assessment enabler, otherwise it was removed. The value of the threshold was computed by the average of minimum value of the important linguistic variable (0.5) and the maximum value of normal (0.7) linguistic variable. It was computed as 0.6 (Kumar et al., 2018; Noori et al., 2020).

**3.3. Interval-valued Fuzzy Analytical Hierarchy Process**

Analytical Hierarchy Process (AHP) is an extensive MCDM method for ranking and assigning weights to criteria and alternatives. The method was firstly introduced by Thomas Satty in 1970. The problem structure of AHP method is usually a multilevel hierarchy. The top level indicates the problem’s goal solution and lower levels show criteria and sub-criteria. The method can easily assign weight to criteria and sub-criteria by pairwise comparison at the given level (Singh et al., 2018). High precision in assigning weight to criteria has attracted many researchers to apply it to research activities (Minatour et al., 2016). The essence of the method is based on pairwise comparison between criteria. The pairwise comparison result at the given level is put down into a decision matrix (6) (Singh et al., 2018):

(9)

Where is indicator of pairwise comparison of criteria and for ( ).

Once the decision matrix is formed, the local importance of criteria is obtained by solving eigenvector of matrix. After calculating local weight of the criteria, global weight of criteria is obtained by integrating local weights with regards to successive hierarchy levels.

Due to the inherent existing uncertainty in some of the criteria and absence of experts’ agreements on linguistic variables and membership function of fuzzy numbers, AHP method with crisp and normal fuzzy numbers was unable to model the ambiguity. Therefore, interval-valued triangular fuzzy numbers were used for modelling the existing uncertainty. The interval-valued fuzzy AHP method stepwise consisted of:

**a. Pairwise comparison of criteria**

A set of pairwise comparison matrices were constructed by collecting data from a limited number of respondents using a questionnaire. The questionnaire enabled respondents to compare the criteria and sub-criteria pairwisely of the linguistic variables shown in Table 4. Then, the variables were converted to interval-valued fuzzy numbers:

**Table 4.** Linguistic variables for comparing enablers’ preference

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Linguistic variables** | **Number** | **Fuzzy Number** |
| 1 | Equal preference | 1 | [(1, 1);1;(1, 1)] |
| 2 | Less preference | 2 | [(1, 2);3;(4, 5)] |
| 3 | Important | 3 | [(3, 4);5;(6, 7)] |
| 4 | More important | 4 | [(5, 6);7;(8, 9)] |
| 5 | Extremely more important | 5 | [(7, 8);9;(9, 9)] |

**b. Data Aggregation**

Since the number of experts exceeded one person, data aggregation was required to turn a set of matrices into a single decision matrix:

(10)

(11)

(12)

(13)

(14)

(15)

(16)

Where is a pairwise comparison of criteria and . , , , and are indicators of the left bound of the upper triangular fuzzy membership function, left bound of lower triangular fuzzy membership function, median bound of fuzzy membership function, right bound of lower triangular fuzzy membership function and right bound of upper triangular fuzzy membership function respectively. shows the number of participating experts expressing their judgments.

**c. Deffuzification**

After creating a single interval-valued fuzzy decision matrix by aggregating the experts’ judgments, the decision matrix was deffuzified by:

(17)

**d. Normalization**

By this step, the crisp decision matrix was already normalized. The value of each element was divided by the addition of each relevant column.

**e. Calculation of relative weight**

The relative crisp weight value of indexes were obtained by:

(18)

(19)

, , …., (20)

Where represents an additional value of each relevant row and is an additional value of the matrix elements. is the final criteria weight value while shows the number of criteria.

**3.4. Fuzzy Evaluation Method**

The Fuzzy evaluation method uses fuzzy mathematic theories and arithmetic fuzzy operations to assess criteria and sub-criteria by assigning a score (Guo and Li, 2019; Ramanayaka et al., 2019). This method was applied in the present research at two levels for assessing such criteria and sub-criteria. The method comprised of the following steps (Ramanayaka et al., 2019):

**Step 1. Assessors:** A group of experts was selected to assess the criteria and sub-criteria. The assessors did not need to be experts.

**Step 2. Questionnaire:** A declarative questionnaire was developed following five verbal scales, i.e. excellent, very good, good, fair and poor. The assessors’ response was assigned a numeric value for turning qualitative into quantitative data as: . The number of assessors was denoted by represented the number of assessors.

**Step 3. Single criteria assessment:** Each criterion was evaluated by the relevant sub-criteria, independently of that shown by the fuzzy vector denoted the number of comments set. The evaluation vector was normalized, where Since each criterion was made of different sub-criteria, all sub-criteria assessment was a fuzzy relationship from to :

(21)

Where represented the grade of membership of sub-criteria for the comment . indicated the number of sub-criteria associated with the criteria .

**Step 4. Evaluation result:** the evaluation result was obtained by multiplying the criteria’s weight vector into matrix of the assessment criteria:

(22)

denoted the assessment result of criteria associated with th element in the comment set.

**Step 5. Deffuzification:** The fuzzy score of sub-criteria and criteria were deffuzified by:

(23)

Where is an evaluation vector. shows comment value.

**4. The Proposed Framework**

In this section, the proposed framework for evaluating Industry 4.0 enablers of CP and CE implementation in the context of business ethics is introduced. After identifying the most adequate enablers, they were validated through the Fuzzy Delphi method. Then, the validated enablers were classified into 6 main enablers and sub-enablers. The validated enablers and sub-enablers were assigned weights by using the IVFS AHP method. The Fuzzy Evaluation Method (FEM) employed to assess the readiness scores of enablers and sub-enablers based on the proposed framework.

The research methodology process followed is illustrated in Figure 1.

**First Phase (Fuzzy Delphi):**

Extracting and finalizing the Industry 4.0 enablers

**Second Phase (IVFS - AHP):**

Assigning weight to enablers and sub-enablers

**Third Phase (Fuzzy Evaluation Method):**

Assessing readiness value of enablers and sub-enablers for a case study

**Figure 1.** Research methodology process followed

**4.1. Validating the identified enablers**

In this step, all relevant studies of Industry 4.0 enablers for the efficient implementation of CP and CE and sustainable ethical development were reviewed and the most commonly stated in the literature were elicited as shown in Table 1. The Fuzzy Delphi method was then applied to collect experts’ opinions through a Likert scale questionnaire to validate the enablers.

After collecting the experts’ judgments, the enablers’ scores were calculated using equations 6 to 8. If the score was higher than 0.6, the enablers were accepted, otherwise, they were omitted (Kumar et al., 2018; Noori et al., 2020). Table 5 shows the final verified Industry 4.0 enablers.

**Table 5.** The validated Industry 4.0 enablers

|  |  |  |
| --- | --- | --- |
| **No.** | **Industry 4.0 enablers** | **Response Score** |
| 1 | Training Employers for better use of Industry 4.0 technologies in the context of business ethics | 0.62 |
| 2 | Assuring security of Industry 4.0 systems | 0.64 |
| 3 | Applying Machine learning systems | 0.61 |
| 4 | Applying flexible Industry 4.0 system | 0.74 |
| 5 | Effective performance metrics for assessing effectivity of CP and CE embedded with Industry 4.0 | 0.76 |
| 6 | Applying effective optimisation techniques | **0.52** |
| 7 | Using Industry 4.0 system for assessing regular tracking of stock and in-process inventory | 0.62 |
| 8 | Applying man-machine interaction | 0.63 |
| 9 | Applying Industry 4.0 supportive policies | 0.78 |
| 10 | Applying Internet of Things | 0.71 |
| 11 | Allocating appropriate budget for fostering Industry 4.0 | 0.85 |
| 12 | Applying smart factory equipment | 0.74 |
| 13 | Management level participation in developing industry 4.0 | 0.73 |
| 14 | Granting reward and incentives policy for faster development of Industry 4.0 | 0.84 |
| 15 | Ensuring employer’s privacy by deploying secure industry 4.0 | 0.88 |
| 16 | Recognizing potential implications of Industry 4.0 | 0.82 |
| 17 | Creating smart supply chain by industry 4.0 | 0.87 |
| 18 | Constant tracking of suppliers by Industry 4.0 system | 0.79 |
| 19 | Knowledge-based decision making in supply chain | 0.78 |
| 20 | Applying Big data | 0.81 |
| 21 | Visual computing | **0.48** |
| 22 | Additive manufacturing | 0.62 |
| 23 | Operational efficiency | 0.77 |
| 24 | Cloud computing | 0.78 |
| 25 | Industrial system integration | 0.74 |
| 26 | Infrastructure building | 0.80 |
| 27 | Applying Block chain | 0.72 |
| 28 | Self-adaptability | 0.76 |
| 29 | Safety | 0.87 |

As shown in Table 5, the vast majority of the enablers’ scores were over the threshold (0.6), therefore, they were considered part of the assessment list of Industry 4.0 enablers for the implementation of CP and CE in the context of an ethical society. Just two enablers’ scores were below the threshold, i.e. “Visual computing” and “Optimization techniques”, so they were omitted from the list. After validating the enablers, they were grouped into 6 categories based on previous studies and experts’ judgments. The final enablers and sub-enablers are shown in Table 6.

**Table 6.** Enablers and sub-enablers of the proposed framework

|  |  |  |
| --- | --- | --- |
| **No.** | **Enablers** | **Sub-Enablers** |
| 1 | Technical capability | Applying Machine learning systems  Applying man-machine interaction  Applying Internet of Things  Creating smart supply chain by industry 4.0  Applying Big Data  Additive manufacturing  Cloud computing  Infrastructure building  Applying Block Chain |
| 2 | Policy and Regulation | Effective performance metrics for assessing effectivity of CP and CE embedded with Industry 4.0  Applying Industry 4.0 supportive policies  Allocating appropriate budget for fostering Industry 4.0  Granting reward and incentives policy for faster development of Industry 4.0 |
| 3 | Education and participation | Training Employers for better use of Industry 4.0 technologies in the context of business ethics and CSR  Management level participation in developing industry 4.0  Recognizing potential implications of Industry 4.0 |
| 4 | Security and Safety | Assuring security of Industry 4.0 systems  Ensuring employer’s privacy by deploying secure industry 4.0  Leveraging the employers’ safety by applying smart components |
| 5 | System flexibility | Applying flexible Industry 4.0 system  Industrial system integration  Self-adaptability |
| 6 | Support and maintenance | Using Industry 4.0 system for assessing regular tracking of stock and in-process inventory  Applying smart factory equipment  Constant tracking of suppliers by Industry 4.0 system  Knowledge-based decision making in supply chain  Operational efficiency |

As shown by Table 6, the proposed framework is comprised of 6 enablers, including Technical capability, Policy and Regulation, Education and participation, Security and safety, system flexibility and support and maintenance. Each enabler is assessed by relevant sub-enablers, see Table 6. The Consistency Ratio (CR) was calculated, resulting in a value of 0.081, which indicated high stability of the decision matrix.

**4.2. Assigning weight to the enablers and sub-enablers**

In this section, the defined enablers and sub-enablers were assigned a weight value using the AHP method. Due to the existing ambiguity in some of the enablers and sub-enablers, Fuzzy sets theory was applied to model such ambiguity. Moreover, due to the absence of experts’ judgments on allocating a single membership function for triangular fuzzy numbers, the membership function was defined in an interval [0,1]. To collect the data, a pairwise-based questionnaire was handed out to 8 experts. The selection criteria for experts included: 1) minimum education qualification must be master in a related area and 2) they must have a minimum of five years of research and/or industrial experience. A group of experts was selected from industry and academia. The vast majority of the respondents had a PhD degree and Master of Science in Industrial Engineering and Information Technology Management. 75 percent of the respondents were male (6 people) and 25 percent of them were female (2 people). The respondents had experienced working in supply chain. 38 percent had more than 12-year of experience, 37 percent had between 8 and 12-year of experience and 25 percent had 8-year of experience in supply chain and information technology. The final results are shown in Table 7.

**Table 7.** Weight analysis

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Enablers** | **Weight** | **Ranking** | **Sub-enablers** | **Weight** | **Ranking** |
| Technical capability | 0.23 | 1 | Applying Machine learning systems | 0.05 | 8 |
| Applying man-machine interaction | 0.03 | 9 |
| Applying Internet of Things | 0.13 | 4 |
| Creating smart supply chain by industry 4.0 | 0.17 | 2 |
| Applying Big data | 0.11 | 5 |
| Additive manufacturing | 0.15 | 3 |
| Cloud computing | 0.06 | 7 |
| Infrastructure building | 0.21 | 1 |
| Applying Block Chain | 0.09 | 6 |
| Policy and Regulation | 0.18 | 3 | Effective performance metrics for assessing effectivity of CP and CE embedded with Industry 4.0 | 4 | 0.14 |
| Applying Industry 4.0 supportive policies | 1 | 0.36 |
| Allocating appropriate budget for fostering Industry 4.0 | 2 | 0.31 |
| Granting reward and incentives policy for faster development of Industry 4.0 | 3 | 0.19 |
| Education and participation | 0.13 | 5 | Training Employers for better use of Industry 4.0 technologies in the context of business ethics | 0.26 | 2 |
| Management level participation in developing industry 4.0 | 0.53 | 1 |
| Recognizing potential implications of Industry 4.0 | 0.21 | 3 |
| Security and Safety | 0.21 | 2 | Assuring security of Industry 4.0 systems | 0.48 | 1 |
| Ensuring employer’s privacy by deploying secure industry 4.0 | 0.31 | 2 |
| Leveraging the employers’ safety by applying smart components | 0.21 | 3 |
| System flexibility | 0.16 | 4 | Applying flexible Industry 4.0 system | 0.36 | 2 |
| Industrial system integration | 0.48 | 1 |
| Self-adaptability | 0.16 | 3 |
| Support and maintenance | 0.09 | 6 | Using Industry 4.0 system for assessing regular tracking of stock and in-process inventory | 0.17 | 4 |
| Applying smart factory equipment | 0.18 | 3 |
| Constant tracking of suppliers by Industry 4.0 system | 0.16 | 5 |
| Knowledge-based decision making in supply chain | 0.23 | 2 |
| Operational efficiency | 0.26 | 1 |

As shown by Table 8, the most important enablers that had the strongest effect on CP and CE implementation within business ethics were “Technical capability” and “Security and safety”, which weight values were 0.23 and 0.21 respectively. Moreover, the least important enablers were “Support and maintenance” and “Education and participation”, which weight values were 0.09 and 0.13 respectively.

**4.3. Readiness Score - Case Study in an Iranian textile manufacturing company**

The proposed framework was deployed in one of the largest Iranian textile manufacturing companies with more than 350 staff. The readiness score of enablers and sub-enablers was obtained by applying the Fuzzy Evaluation Method. In the first step, a questionnaire was distributed among a group of assessors to select a linguistic variable (i.e. excellent, very good, good, fair, poor).

The readiness value was a number between zero and one hundred. The higher the value, the higher a company’s readiness of enablers and sub-enablers. Thus, the collected data indicated the readiness score of the enablers, sub-enablers and overall readiness of the case company. The assessment of the enablers and sub-enablers was conducted by 6 assessors from the company’s employees. Based on the framework’s approach, they were asked to select a linguistic variable (i.e. excellent, very good, good, fair, poor) in order to express their judgment regarding the degree of development of the Industry 4.0 enablers in their companies. The user’s comments were aggregated and set into a matrix. For instance, the “Education and participation” enabler was made of 3 sub-enablers. When “Training Employers for better use of Industry 4.0” was considered, 27 percent of the employees marked “Very Good”, 29 marked “Good”, 16 percent marked “Fair” and 28 percent marked “Poor”. On the other hand, when “Management level participation in developing industry 4.0” was considered, 57 percent of the employees marked “Very Good”, 32 percent marked “Good” and 11 percent marked “Fair”. Finally, when “Recognizing potential implications of Industry 4.0” was considered, 15 percent of the employees marked “Very Good”, 12 percent marked “Good”, 29 percent marked “Fair” and 44 percent marked “Poor”, hence an “Education and Participation” enablers matrix was created as:

Then the evaluation result of Education and participation was calculated by:

Similarly, the result of the enablers was calculated and put into the evaluation matrices. Finally, the comprehensive overall evaluation matrix was calculated by:

=

The appraisal vector was deffuzified using equation 23: . The overall readiness score of Industry 4.0 enablers in CP and CE implementation of the Iranian textile manufacturing company studied was computed as 43.45, which is in “Fair” status. The rest of the readiness score of enablers were calculated in the same manner. Such readiness scores are presented in Table 8 and illustrated in Figure 2.

**Table 8**. Readiness score of enablers in the case organisation

|  |  |  |
| --- | --- | --- |
| **Enablers** | **Readiness Score** | **Current Status** |
| Technical capability | 35.66 | Fair |
| Policy and Regulation | 41.35 | Fair |
| Education and participation | 66.78 | Good |
| Security and Safety | 55.86 | Good |
| System flexibility | 37.04 | Fair |
| Support and maintenance | 40.48 | Fair |

**Figure 2.** The readiness score of enablers in the case study

As shown by Table 8, Technical Capability, Policy and regulation, System flexibility and support and maintenance are in “Fair” condition as their readiness scores were computed as 35.66, 41.35, 37.04 and 40.48 respectively. Two enablers Education and participation and Security and safety were in “Good” status as their readiness value was obtained as 66.78 and 55.86 respectively.

**5. Results and Discussion**

In this paper, a novel framework for assessing the Industry 4.0 enablers in the implementation and development of CP and CE in the context of ethical business development was proposed and validated. The framework is comprised of 6 enablers and 27 sub-enablers. The framework clarifies the preference of enablers and sub-enablers by assigning them a weight between zero to one. The final results of the framework after it was applied in Iranian textile manufacturing company are presented in Table 8.

The most significant enabler was determined to be “Technical Capability”. The enablers mostly concentrated on the application of cutting-edge technologies in regards to the better implementation and development of CP and CE. The highly significant importance of these enablers is supported by Gmelin and Seuring (2014), Hong et al. (2019) and Katiyar et al. (2018). The most important sub-criterion was Infrastructure building, which is responsible for providing an appropriate platform for facilitating further development of potential technologies. Since the main aim of Industry 4.0 is to provide a smart supply chain for the better implementation of CP and CE, providing a smart supply chain was the second most important sub-criterion. Additive manufacturing resulted to be the third most important sub-enabler. Additive manufacturing accelerates manufacturing processes by creating 3D objects. It has a direct impact on the effective and efficient performance of operations and the faster implementation of CP and CE. Industry 4.0 involves different technologies that can contribute to a better and faster implementation of CP and CE. The most important technologies include IoT, Big Data, Block chain, Cloud Computing and machine learning respectively. The least important sub-criterion was Man-machine interaction. It intends to facilitate the interaction between humans and machines for better use of robots and systems by users.

The second most important enabler was Security and safety, which aims at providing secure infrastructure to exchange critical data and avoid data leakage. Moreover, employer’s safety and privacy were also taken into account as important factors. Providing a safe and secure platform to keep data privacy is the main dimension of business ethics to clear the way for suppliers to behave ethically in the business environment. Such practices increase trust and commitment among suppliers, which causes to leverage sustainability in SCM. The high importance of the enabler has been highlighted by Seuring et al. (2019), Pham et al. (2019) and Xu et al. (2016); Yun et al. (2019); Mirghafoori et al. (2018). The most important sub-enabler was assuring staff and employers regarding the security of Industry 4.0 technologies and systems. Such an issue has a direct effect on accelerating and facilitating the development and implementation of CP and CE and evolving ethical principles for sustainable development. Assuring staff privacy by creating a secure platform without any potential data leakage is critical for the faster development of Industry 4.0 in SCM. One of the most important Industry 4.0 responsibilities is leveraging the staff’s safety by using smart components in supply chains and operations. This, however, was considered as the least important sub-criterion.

Policy and regulation was the third most important enabler. The policy and regulation enabler is responsible for formulating and deploying new legislation, e.g. budget allocation and passing new rules for utilizing Industry 4.0 technology more effectively. Even from an ethical perspective, setting ethical policies and regulations is one of the most important aspects of corporate social responsibility, which helps to increase business ethics to leverage sustainability in SCM. The high significance of this enabler has been emphasised by Hong et al. (2019), Mani et al. (2018) and Stoycheva et al. (2017); Yun et al. (2019). Since Industry 4.0 is seen as a new phenomenon in the world of technology, setting an appropriate policy for better guidance of potential users is critical. Thus, this is considered as the most important sub-enablers. Further development of Industry 4.0 enablers in the implementation of CP and CE requires sufficient budget. This was listed as the second most important sub-enabler. Making reward and incentive policy is a great tool for motivating employers to pay more attention to such a new phenomenon and creating sustainable ethical development. Encouraging suppliers to behave ethically in the business environment by providing incentives and prizes is highly required for enhancing the entity’s reputation and sustainability in SCM. Constant assessment contributes to evaluating the current status of Industry 4.0 enablers in the implementation of CP and CE and ethical societal sustainability. It resulted to be the least important sub-enabler.

System flexibility was considered the fourth most important enabler. It assesses the Industry 4.0 system’s flexibility to be integrated with already operating systems. The high importance of this enabler has been highlighted by Rajput and Singh (2019) and Xu et al. (2016). System integration was the most important sub-enabler, which assesses the current system’s ability to be integrated with Industry 4.0 systems to provide a more comprehensive system. Such system integration has a direct effect on the further development and faster implementation of CP and CE. Providing an integrated system depends on applying flexible Industry 4.0 technologies. This is conducive to CP and CE implementation, which is seen as the second most significant sub-criterion. The least important sub-enabler was self-adaptability. This sub-enabler evaluates the current system’s ability to adapt itself with Industry 4.0 systems.

As industry 4.0 technology is a new phenomenon and hence there is still a lack of information about some of its characteristics, Education and participation are highly required to enhance employee’s awareness and involvement (Seuring et al., 2019; Moktadir et al., 2018). Top-level management is a significant factor for applying Industry 4.0 in CP and CE implementation and developing ethical principles. This sub-enabler mostly assesses the top management’s commitment and support to use Industry 4.0 technologies in supply chain operations. Exposing employees to regular training courses has a direct effect on increasing their knowledge about such a new phenomenon, which consequently causes them to increase their participation. Moreover, effective training increases personal staff value to behave ethically through the entire supply chain. Consequently, this is likely to enhance sustainable SCM (Yun et al., 2019). Recognizing the potential implication of Industry 4.0 enablers was the least important sub-enabler. This is seen as an important tool for motivating and informing employees about the prospective benefits of Industry 4.0 utilization in the implementation of CE and CP.

The least important enabler was Support and maintenance. This enabler concentrates on the tracking of suppliers and stock. The high importance of such enabler has been discussed by Schwab et al. (2019) and Seuring et al. (2019). The most important sub-enabler was Operational efficiency, which assures managers that supply chain processes are working efficiently and effectively. Industry 4.0 paves the way for collecting and analysing a huge amount of data. Such refined collected data let managers make decisions more logically and precisely. One of the main targets of Industry 4.0 technology is creating a smart factory, which components work automatically to increase performance efficiency and effectiveness. Such an issue facilitates the implementation of CP and CE and creates more sustainable social business development. Constant and regular tracking of stock and suppliers are the least important sub-enabler.

**6. Research Implications**

**6.1. Implications for theory**

The current study derives three main theoretical implications, including:

* Various studies have emphasised the importance of Industry 4.0 enablers in facilitating the sustainable implementation of CE and CP and their development (Devi et al., 2020; Rajput and Singh, 2019). However, these studies have considered limited aspects of Industry 4.0 enablers concerning the effective implementation of CP and CE in the context of an ethical society. Thus, such studies abstain from providing precise results and outcomes. The main theoretical implication of the present work is the proposal of a framework that considers broader aspects of Industry 4.0 enablers embedded with CP and CE implementation for sustainable ethical development. The framework considers various enablers and sub-enablers aimed at providing a more exact and meticulous assessment compared to previous studies.
* The literature review denoted that previous studies mostly introduced different efficient Industry 4.0 enablers for digitalizing CP and CE for reaching ethical sustainable societal development. There are no studies to recognize the importance and preference of enablers in the implementation of CP and CE in the context of ethical social responsibility. In this study, the importance and preference of enablers were obtained and ranked by Multi Enablers Decision Making.
* The study considered business ethics in the implementation of CP and CE. The significant importance of ethical behaviour and Corporate Social Responsibility was highlighted to achieving a more sustainable SCM. Moreover, the study has denoted that constantly training staff and keeping their privacy lead to ethical behaviour of suppliers, which helps to increase sustainability in the entire supply chain.
* The proposed framework suggests that a sustainable supply cannot only be achieved through the application of Industry 4.0 in CP and CE implementation. Business Ethics and CSR principles have to be considered for reaching long-lasting sustainability in supply chain practices.
* Some Industry 4.0 enablers are subjective and contain a high level of uncertainty. Previous studies mostly used statistical methods to find any relevant association between Industry 4.0 enablers and the sustainable implementation of CP and CE. Nevertheless, such research methodology cannot appropriately model enablers’ ambiguity. Thus, Fuzzy sets theory was applied to capture the enablers vagueness.

**6.2. Implications for practice**

The present study has significant practical implications for business managers, including:

* The paper highlights the important role of Industry 4.0 enablers for a better and faster implementation of CP and CE. This may encourage industrial managers to consider Industry 4.0 enablers in their business decisions. The study opened up various aspects of Industry 4.0 enablers to enhance the sustainable implementation of CP and CE in the context of business ethics and supply chains performance and efficiency. The main Industry 4.0 enablers were defined as 6 enablers that included technical capability, policy and regulation, education and participation, security and safety, system flexibility and support and maintenance. The most important element that managers should consider is the technical capability of their organisations, which urges them to apply cutting-edge technologies including IoT, Big Data, Blockchain and Machine learning to achieve a sustainable implementation of CP, CE and ethically sustainable business development. The integration of Industry 4.0 applications (such as IoT, Big and Blockchain) in supply chains has a direct impact on production efficiency and environmental management. Industry 4.0 tools enable managers to easily fulfil more sustainable production and consumption goals. For instance, the application of Industry 4.0 technologies such as IoT and Big Data Analytics in Indian organizations has brought a better performance of supply chains and sustainable business development (Singh et al., 2019). Moreover, the significant application of Internet of Things (IoT) in enhancing circular economy was proven in the food industry in the Netherlands (Ingemarsdotter et al., 2020). The second most important factor that is expected to be considered by industrial managers is creating an appropriate infrastructure to embed Industry 4.0 technologies. Since Cleaner production is considered a business strategy (Hens et al., 2018), providing a robust and strong infrastructure paves the way for policymakers and managers to accelerate the strategy aimed at improving better process monitoring and product or service design. For instance, Indian manufacturing firms denoted that applying appropriate building infrastructure makes the supply chains and CE implementation more agile and sustainable when embedded with Industry 4.0 technologies (Rajput and Singh, 2019).
* Since a huge amount of information is created during supply chain operations, including employees and company’s information, keeping them confidential is the responsibility of business managers to avoid any potential data leakage by providing a secure platform for data transactions. Observing information privacy is a critical social responsibility of policymakers and managers. Keeping information privacy is considered as an ethical behaviour that leads to higher sustainability in supply chains. Such behaviour helps policymakers to keep the reputation of corporations as an ethical image, which causes to increase trust and commitment between supply chain actors (Mirghafoori et al., 2018). They should integrate such cutting-edge technologies with CP while evolving ethical principles of corporate social accountability by observing privacy. Such an issue would assure users that their confidential information is not at risk of being abused. Symeonidis et al. (2019) proved that data protection and privacy are two important non-technical factors for the sustainable development of circular economy and sharing economy. This has been highlighted in other contexts in terms of Industry 4.0 integration with CE. For instance, keeping the medical records of patients confidential was highlighted when IoT technologies were embedded with circular economy for a better analysis of patients’ information (Hatzivasilis et al., 2019). Moreover, CP includes improved workers’ health and safety (Fatorachian and Kazemi, 2018). The application of Industry 4.0 makes a strong contribution to the better monitoring of workers and staff aimed at avoiding potential danger. Business managers should enhance staff safety by using smart technologies.
* Owing to the new concept of Industry 4.0 and lack of any regulation and policy in supply chains operations, legislating appropriate and suitable policy and regulations are managers’ accountability for providing a better framework to use Industry 4.0 enablers more effectively in the implementation of CP and CE. For instance, a study showed that policy and regulation played a crucial role in the better integration of Industry 4.0 and CE implementation in the context of glass recycling for more effective performance (Lin, 2018).

From a business ethics perspective, setting ethical policy and regulation is one of the main pillars of CSR and business ethics, which has a direct and constructive impact on operational efficiency and financial benefit. One of the main manager’s responsibilities is setting up ethical and moral legislation. Policymakers are highly expected to conduct regulations and effective policy following ethical and social principles. This is seen as an inseparable aspect of CSR to reach sustainability in SCM. For instance, China intended to legislate ethical standards as a government policy to create more sustainability in SCM (Yun et al., 2019).

* Due to the absence of rich and publicized information regarding Industry 4.0, it is the managers’ responsibility to expose staff and employees to such new phenomenon by holding different workshops and courses aimed at enhancing their awareness and knowledge. Moreover, such action would lead to higher involvement of employees in applying Industry 4.0 in CE and CP implementation in the context of ethical sustainable business development. Employee’s involvement in CP and CE implementation is another ethical and social responsibility of managers, which can be facilitated by Industry 4.0 applications and tools. For instance, the significant role of education and training for providing more sustainable supply chains development in the context of Industry 4.0 technologies embedded with CE was highlighted by Ramakrishna et al. (2020).

Exposing staff to regular training activities is another main pillar of social responsibility, which informs employers with ethical behaviour within the business environment. Such practices can have a direct effect on the entire supply chain to behave morally and ethically. Ethical practices are likely to bring more commitment and trust between suppliers. This can enhance sustainability within supply chains. For instance, regular training of staff made a strong contribution to increasing personal staff value in SCM within the Indian context, which led to behaving ethically and morally as well as leveraging sustainability in the supply chain (Yun et al., 2019).

* Support and maintenance of CP and CE implementation is another critical factor which can be facilitated by Industry 4.0 tools and applications. Providing constant support and maintenance by application of Industry 4.0 leads to sustainable process monitoring and the enhancement of production efficiency.

**7. Conclusions**

Many manufacturing businesses have experienced significant transformations and changes in their operational processes due to the adoption of Industry 4.0 technologies. Thus, businesses are considering Industry 4.0 technologies as a key influencing enabler to achieve sustainability and support the implementation of Cleaner Production (CP) and Circular Economy (CE) practices to enhance the quality of their products and services within the context of ethical and sustainable business development. Industry 4.0 has shown to facilitate the implementation of CP and CE as well as being a potent contributor to enhance sustainability through business ethics. In this paper, a novel framework was proposed to illustrate the important role of Industry 4.0 enablers in the implementation of CP and CE within business ethics. Firstly, the most important enablers were defined and validated through the Fuzzy Delphi method. The validated enablers were categorized into 6 enablers that included “Technical Capability”, “Policy and Regulation”, “Education and Participation”, “Security and Safety”, “System Flexibility” and “Support and Maintenance”. The importance of the validated enablers was established through the IVFS AHP method. The most important enablers were “Technical capability”, Security and safety”, “Policy and Regulation”, “System flexibility”, “Education and participation” and “Support and maintenance” respectively. The results of the framework denote that technical capability is the most important enabler for the successful adoption of CP and sustainable development. The main practical implication derived from this finding is associated with the enhancement of technical infrastructure and capability, including Industry 4.0 technologies such as Big Data and IoT for accelerating the CP implementation and development. Practical implications urge policymakers and managers to reconsider current technical capabilities and apply Industry 4.0 technologies for accelerating CP and CE adoption and development. Such new technologies required supply chain players to behave ethically and follow up corporate social responsibility principles which end up in more sustainable SCM. The proposed framework can be applied in different scenarios to recognize the readiness score of enablers and sub-enablers by using the Fuzzy Evaluation Method. In this study, the proposed framework was applied in a large Iranian Textile manufacturing company to assess the Industry 4.0 enablers in the implementation of CP and CE. The final results showed 43.45 as the total readiness score of the case company, which indicate a “Fair” status in this respect.

The present study has some limitations. Firstly, the Industry 4.0 enablers that play a significant role on the adoption of CP and CE practices in the context of ethical business development were identified by conducting an extensive literature review and validated with inputs from subject experts. In future studies, empirical research can be conducted to define such enablers and determine their “real” impact on various measures of sustainability performance. Secondly, the proposed framework was deployed in an Iranian textile manufacturing company. Regional or inter-industry studies can therefore be conducted to validate such factors and apply the proposed framework considering the influence of specific regional and sectoral characteristics, e.g. policymaking, culture, industry sustainability maturity, etc. This would allow researchers to obtain a clearer picture of the generality of such enablers and contribute to the further validation of the proposed framework. Thirdly, the Interval-Valued Fuzzy Sets (IVFS)-AHP method was used to calculate the priority weights of enablers and sub-enablers. In this line, a comparative study can be conducted by using other multiple-criteria decision-making methods such as Best Worst Method, Decision Making Trial and Evaluation Laboratory. This would allow future researches to understand more about the comparative influencing weights of the enablers. Finally, the proposed framework demonstrated the importance of Industry 4.0 enablers in the adoption of CP and CE. However, there is no information regarding the association and inter-relationship between enablers. Thus, researchers can extend the present study by illustrating the inter-relationship between enablers through structural techniques such as Structural Equitation Modelling, and Analytical Network Process methods.

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