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Impeding Challenges on Industry 4.0 in Circular Economy: Palm oil industry in Malaysia

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1. Introduction

The demand for palm oil is increasing due to the increase in domestic oilseed supplies in the top buyer, India, and increased demand in Europe and China. The palm oil production process requires that more arable land be converted to palm oil plantations and generates greenhouse gas emissions. Thus, to reduce waste and greenhouse gas emissions, Industry 4.0 (I4.0) digital technologies, including sensing, computing and communicating systems in the management of energy grids, transportation and manufacturing, have permeated palm oil production process systems (Dranka & Ferreira 2020; Ourahou et al. 2020; Tseng et al. 2018). The I4.0 application eventually reduces production waste and monitor operational and production processes to balance social impacts, reduce environmental risks and increase economic benefits. In addition, circular economy (CE) could maximize the circularity of resources and energy within production systems, thus preventing the waste of natural resources (Geissdoerfer et al. 2017; Ghisellini et al. 2016). For instance, Hofmann and Rüsch (2017) presented I4.0 assistance to highlight and enhance reduced waste and resource consumption. It also improves real-time information, end-to-end supply chain transparency and flexibility, thus helping palm oil firms optimize economic benefits (Hofmann & Rüsch 2017; Tseng et al., 2018).

Prior studies have shown that I4.0 guides firms to new technology transformations and creates enhanced value by enabling them to achieve long-term competitiveness and accommodate business environmental changes (Ghobakhloo & Ching, 2019; Hofmann & Rüsch, 2017; Rajput & Singh, 2019). However, these technology transformations make I4.0 complicated and create many challenges. For instance, O'Donovan et al. (2019) reported that there are genuine limitations regarding consistency, reliability and external risk attributes in I4.0 technology applications that challenge existing practices. In particular, Ghobakhloo and Ching (2019) and Horváth and Szabó (2019) proved that technology innovation demands higher investment, as new technologies must be properly tested and optimized. Dalmarco et al. (2019) highlighted that the main challenge in I4.0 is to interconnect the new technology with all process technologies, including the available equipment and workforce, since current technologies continue to need additional development in each production process. In contrast, Büchi et al. (2020) confirmed that the use of I4.0 technologies can increase production capability, decrease errors and costs, provide greater opportunities in terms of flexibility and speed, improve product quality and enable a company to meet customer needs. However, the research on I4.0 is still in the nascent stage, when studies of its effectiveness remains scattered and fragmented, and there are few practical examples in the palm oil industry (Babiceanu & Seker, 2016; Horváth & Szabó, 2019; Rosa et al. 2019). This study considers such I4.0 challenges and practices to realize the new technology transformation with the help of CE benefits.

Improper usage of materials and energy causes finite resources to become scarce (Lieder & Rashid 2016; Ngan et al. 2019), and CE benefits include reducing negative environmental degradation, increasing economic benefits and reducing sustainability pressure by incorporating reduced, recycled and recovered resources into the system (Ghisellini et al., 2016; Kirchherr et al., 2017; Winans et al., 2017). Prior studies have argued that CE has failed to develop the technology needed to deal with the recycling process and reduce the resources needed (Kinnunen & Kaksonen 2019; Su et al. 2013; Tura et al. 2019). For instance, Su et al. (2013) stated that the lack of information on the product life cycle and a shortage of advanced technologies for cleaner production have diminished CE benefits. Heyes et al. (2018) highlighted that CE recycled technologies have a limited ability to recover resources, which has caused resource recovery to remain relatively low, and promising CE benefits are difficult to achieve. Kinnunen and Kaksonen (2019) claimed that technology development in CE is low and slow due to the difficulty of developing such technology while considering profit and usability in terms of intensive investment. Tura et al. (2019) emphasized the expense of the initial investment in CE technology development, followed by uncertainty regarding the time needed for CE implementation and return on investments; these issues often result in reluctance to adopt CE approaches. However, Gigli et al. (2019) argued that the use of technology in the CE recycling process can increase economic profitability, which helps a firm become more economically sustainable. This study is essential to bridge the gaps, while I4.0 in CE in terms of the technology involved could enable recycling, reuse and reduction in the production process.

I4.0 in CE is the production process, which is a complicated process due to the need for valid measures and the complicated relationships among the attributes (Bui et al. 2020; Noorderhaben 1995). Prior studies have presented various attributes of I4.0 and CE (Babiceanu & Seker, 2016; Horváth & Szabó, 2019; Ormazabal et al., 2018). For instance, Babiceanu and Seker (2016) applied algorithmic analytics to identify the current status of I4.0 technology in manufacturing operations. Leitão et al. (2016) analysed the key aspects of I4.0 and uncovered potential opportunities and challenges. Ormazabal et al. (2018) determined the degree of CE implementation, including willingness to work with others, and the barriers and opportunities that may arise in CE implementation. Horváth and Szabó (2019) employed in-depth interviews with leading members of firms to determine the driving forces and challenges of I4.0. In reality, it is difficult to determine perceptions and judgements from quantitative information. This study applied the fuzzy Delphi method (FDM) to screen out the less important attributes, and the attributes are described in terms of qualitative information and access with linguistic preferences. The FDM addresses qualitative information and translates linguistic preferences to comparable values. In practice, this study applies interpretive structural modelling (ISM) to analyse the inter-relationship among the criterion that influence the challenges of I4.0 in CE that were derived earlier.

This study investigates how to impede the challenges to I4.0 in CE in the palm oil industry. The contributions of this study are as follows: (1) collecting and verifying a valid and reliable set of challenges to I4.0 in CE and (2) providing evidence that empirically verifies the challenges to I4.0 in CE. This study addresses a gap in the existing knowledge and provides insight into the challenges to I4.0 in CE, as the adoption of I4.0 in CE is relatively new. In practice, the findings help managers establish clear expectations with regard to the challenges to I4.0 in CE. The palm oil industry can obtain promising solutions from identifying the challenges to I4.0 in CE to induce symbiotic relationships in business firms. The findings also provide an opportunity to customize the technology of I4.0 in CE. The remaining parts of this study are as follows. Section 2, the literature review, provides details of the theoretical background of I4.0 in CE, the proposed method and the proposed measures. Section 3 discusses the method used in this study, while the results of the study are presented in Section 4. Section 5 discusses the study's implications. Finally, the limitations and directions for future research are presented in the last section.

2. Literature Review

This section discusses I4.0 and CE to provide a sufficient understanding of the challenges. It also addresses the proposed measures and assessment method.

2.1 Theoretical Background

I4.0 represents the Internet of Things (IoT), big data and cloud computing, which are associated with a number of concepts, tools and methods that have the ability to radically change modern society and industry. Luthra and Mangla (2018b) stated that I4.0 is a recent concept that is still unfolding in emerging economies. Thus, firms lack knowledge for appropriate I4.0 implementation, as proper and conscious planning is strictly needed from the beginning of implementation (Horváth & Szabó 2019; Rymaszewska et al. 2017). Tortorella et al. (2020) emphasized that the promising benefits offered by I4.0 technologies is more systematically acquired when firms facilitate learning and knowledge sharing at an organizational level. Conversely, Frey and Osborne (2017) claimed that I4.0 would cause a loss of 47% of jobs in a decade or two, as many jobs currently performed by humans performed by computers. However, Balsmeier and Woerter (2019) proved that I4.0 creates new job opportunities for high-skilled workers, while medium- and low-skilled workers need to learn new skills that enable them to take over new tasks at the end of the production process. Due to the rapid development and innovation of I4.0, diverse points of view exist, in turn creating a set of challenges that make practice complex. An interdisciplinary approach to I4.0 in CE is necessary because CE is a closed-loop chain that focuses on enhancing resource efficiency and environmental performance (Heyes et al. 2018).

Many studies have attempted to integrate I4.0 and CE (Dev et al. 2020; Rajput & Singh 2019; Tseng et al. 2018). For instance, Rajput and Singh (2019) found that the integration of I4.0 and CE increased operational productivity, enhanced efficiency and accuracy, and thus improved sustainability in the supply chain. Dev et al. (2020) suggested a roadmap to operational excellence in terms of the integration of I4.0 informational technologies and reverse logistics-oriented CE. In addition, from the customer perspective, Heyes et al. (2018) reported that CE increases customer satisfaction by shifting the firm focus from a product-oriented approach to a user-centred eco-design. Winans et al. (2017) highlighted that it is necessary to know the quality of materials circulating within production systems to increase customer satisfaction. In addition, firm willingness to invest has been identified as a major constraint on full CE implementation. For instance, Ormazabal et al. (2018) revealed that CE cannot help firms increase profitability and sustain their market position, whichmakes firms hesitant to invest in the needed materials and technology. In addition to the high initial investment, several scholars have found that firms are not willing to make any investment, as there is a lack of knowledge about return on investment (Fischer & Pascucci 2017; Kinnunen & Kaksonen 2019; Tura et al. 2019). This finding indicates that CE approaches fail to provide a big picture of the economic benefits of digital investment and convince firms to invest. Su et al. (2013) suggested that the government must take action and responsibility to increase investment and development in order to improve technological innovation in CE.

Luthra and Mangla (2018) emphasized that I4.0 helps to improve process safety, such as resource efficiency, employee and community welfare, and smarter and more flexible processes in supply chains. This argument indicates that I4.0 technologies have the capability to pave the way for CE. As I4.0 in CE is a recently emerging technological innovation idea, these two emerging topics have not been widely explored and analysed.

Theoretically, I4.0 in CE must be capable of handling waste production, and ongoing changes on a global level have led to a networked society, affecting both business and private life. However, these applications are not easy to implement because they require a high operational cost, which is always a major cause of reluctance because profitability is uncertain and efficiency and effectiveness are blurred (Dev et al. 2020; Rajput & Singh 2019). Hence, it is critical to indicate the challenges to I4.0 in CE to successfully implement it and gain the associated social, economic and environmental benefits.

2.2 Proposed Method

Prior studies have offered different methods to evaluate the inter-relationship between aspect, I4.0 and CE (Büchi et al. 2020; Horváth & Szabó 2019; Tura et al. 2019), and only a few studies have applied linguistic preferences (Vafadarnikjoo et al. 2018). To indicate the challenges to I4.0 in CE, this study proposes using an FDM to screen out the less important attributes, and the attributes are described in terms of qualitative information and access with linguistic preferences. The traditional Delphi method has obvious weaknesses, including its subjectivity and time-consuming nature (Pill 1971). To overcome these shortcomings, the FDM developed by Murray et al. (1985), which combines fuzzy theory and the Delphi method, is proposed. In FDM, the experts' judgements are represented by fuzzy numbers. Then, the subjective opinions are transformed into objective data through fuzzy operations. The FDM comprehensively considers the uncertainty and ambiguity of the experts' subjective thinking so that each expert's opinion is fully reflected in the decision (Sadeghi et al. 2016; Tseng et al. 2018). This approach transforms human linguistic perceptions into a measurable scale using fuzzy set theory. Thus, the results are objective and reasonable. In practice, this study also proposes applying ISM to confront the influential practical challenges to I4.0 in CE.

The FDM has been widely employed. Kou et al. (2014) used it to collect the attribute weights of disaster assessment indices through a questionnaire survey. Zhang (2017) used the FDM to suggest the most suitable low-carbon tourism strategy. Vafadarnikjoo et al. (2018) used the FDM to explore the major motivational attributes for buying a remanufactured bike. Chen et al. (2018) exploited the FDM to obtain an important indicator for a sustainable school ground environment. This method has also been used by some authors to screen the evaluation criteria, and the converged interval-valued triangular fuzzy numbers-grey relation analysis weight method handles the vagueness of system uncertainty and incomplete information with interdependence relations (Tseng, Lim, et al. 2018). Bui et al. (2020) applied this method to identify the top crucial sustainable solid waste management barriers and provide practical suggestions. ISM provides a sequence of criteria that influence other criteria in the complicated inter-relations of complex issues or problems. For instance, Luthra and Mangla (2018) conducted ISM to determine the relationship among the identified strategies in sustainable supply chain management. This study applies the FDM and ISM together to develop valid attributes and construct a hierarchical structure.

2.3 Proposed I4.0 in CE challenges

Since there has been minimal research on the palm oil industry in assessing I4.0 in CE, prior measures available from other industries are adopted. A new set of measures, e.g., skills, capabilities, and technology, is developed in an English version to address the challenges to I4.0 in CE. This study contributes to integrating 30 challenges to I4.0 in CE identified through the literature and from experts in the palm oil industry; hence, assessing the challenges is a challenging task that is undertaken on a continuous basis.

I4.0 is currently linked to cyber-physical systems, cloud computing, the IoT and big data. The IoT integrates various sensor devices to communicate with one another. Alaba et al. (2017) emphasized that a lack of security and privacy issues is a barrier to I4.0, as a huge amount of information flow poses a cybersecurity threat and creates data privacy issues. Moreover, Babiceanu and Seker (2016), in reviewing the current status of virtualization and cloud-based services for manufacturing systems, identified a lack of automation system virtualization as one of the main I4.0 challenges. This means that the mechatronic aspects (the physical part of an automated object) and the automation software (the cyber part of an automated object) are not yet reconfigurable. Additionally, Chen (2017) presented perspectives on and enablers of manufacturing in I4.0 and proposed four challenges to I4.0, namely, lack of closed-loop control, which interlinks analytics and actuation for the next generation of intelligent manufacturing; lack of a knowledge base, which is still the bottleneck in implementation; lack of a legacy IT infrastructure, as the infrastructure must be re-evaluated or replaced to meet the needs of the new manufacturing paradigm; and lack of standardization for integrating different elements, including hardware and software.

Frey and Osborne (2017) described the impact of emerging I4.0 technologies and automation on labour market outcomes and found employment disruptions that result in human job losses. In the same vein, Hofmann and Rüsch (2017) emphasized that the concept of I4.0 is not fully established, which causes a lack of understanding of I4.0 implications in practice. Regarding the viewpoint of top executives, I4.0 challenges were identified by Horváth and Szabó (2019), who reported that the challenges were data insecurity, financial constraints, high investment, lack of capabilities to reconfigure production patterns, lack of collaborative I4.0 models, lack of data analysis, lack of global standards and data sharing protocols, low management support and dedication, poorly defined company digital operations vision and mission, unclear economic benefits of digital investments, unstable connectivity among companies, lack of leader experience, lack of integration of technology platforms, lack of organizational and process changes, lack of skills and qualifications and lack of technological infrastructure. In addition to technological barriers, management expectations and organizational functions play a vital role in I4.0 adoption.

Regarding technology and the emergence of a direction, Leitão et al. (2016) presented the challenges as lack of compatibility to keep the system components working together; lack of infrastructure and internet-based networks, which is crucial in effective adoption of I4.0; lack of infrastructure standardization, as infrastructure is required to equip the advance technologies; and lack of process design, including cyber-physical systems-enabled landscapes. Prior studies have revealed a lack of knowledge management systems, limiting manufacturers' ability to plan and develop services based on the actual usage of products by end customers. This knowledge is needed to improve collaboration, locate knowledge sources, and capture and use knowledge to enhance the knowledge management process (Rymaszewska et al. 2017). Yan et al. (2014) indicate that the lack of a solution for effective communication and signal coverage may act as a significant barrier for various products and services. Hence, a lack of internet coverage and IT facilities impacts the implementation of I4.0.

3. Method

This section describes the background of the Malaysian palm oil industry. Then, the FDM and ISM are explained, and the analytical steps are discussed. Figure 1 presents the details of the proposed research work flowchart. Ultimately, this study follows the flowchart to build the hierarchical model.

3.1 Industrial background

The palm oil industry is an important contributor to the Malaysian economy. Over the past decade, many technologies have been tested to remove excess organic and inorganic nutrients from palm oil mill effluent (POME), which cause serious environmental hazards if discharged directly into the environment (Aziz & Hanafiah 2020). In Malaysia, the preferred method of treating POME is the conventional ponding system (Mahmod et al. 2017). Unfortunately, this technique has limitations (Abu Bakar et al. 2018; Ng et al. 2019). Truckell et al. (2019) emphasized that biofertilizer can serve as a local CE approach to deal with the production of a large volume of residues in palm oil mills. Jamaludin et al. (2019) also suggested recycling water as a mitigation option to represent sustainability and simultaneously preventing greenhouse gas emissions by using an integrated palm oil mill carbon footprint accounting and sustainability index method. Foong et al. (2019) found that optimizing oil palm plantation operation using an input-output model greatly improved sustainability and reduced plantation area by 24% with a significant drop in greenhouse gas emissions. However, the application of these practices requires efficient technology to support data storage and advance information availability and technology. This study is important for the palm oil industry to obtain an efficient and effective solution for the continuous and large-scale treatment of POME waste.

Several CE work has been carried out in Malaysia. According to Derman et al. (2018) oil palm mills generally generate numbers of biomass wastes which is transformed into five types of biomass energies: i.e. biogas, bio-fuels, bio-power, bio-oil, bio-char and composts. These biomasses have high potential of turning into renewable energy. For instance, oil palm biomasses have been modified and processed to produce molded oil palm products that extremely versatile and is used in furniture, building, electronics, packaging and automobile industries (Shuit et al. 2009). Besides this, biogas production from POME waste has become a promising sources to potentially boost up the renewable energy sector for sustainable power generation (Chin et al. 2013; Aziz & Hanafiah 2020). In addition, bioethanol production from biomass utilization is an environmentally friendly fuel and has the potential to reduce environmental pollution and consumption of crude oil (Derman et al. 2018). Despite its wide use already, there is still much to be done to optimize the utilization of biomass for cogeneration in Malaysia.

I4.0 technology innovation is a recent concept that has emerged and permeated industry because it helps to improve the efficiency and effectiveness of the production process. The technological advances of I4.0 create possibilities for improving the production process through the integration of intelligent and automated mechanisms into the industrial environment. With technology innovations, I4.0 makes use of resources more efficiently, enabling reduced energy consumption, improved logistics and increased capacity. On the other hand, CE also offers various social, economic and environmental benefits. Recycling and reverse logistics are the most common practices applied to reduce resource consumption and waste production. However, the lack of investment and lack of profitability evidence impeded these applications, and the palm oil industry has not developed an approach to improve sustainability. It is necessary for the palm oil industry in Malaysia to overcome these challenges to achieve sustainability. Hence, this study can help practitioners achieve a higher level of sustainability by identifying the challenges to I4.0 in CE. This study consulted a group of 14 experts: 4 academicians, 6 experts from the government sector and 4 experts in palm oil daily operations. These experts have extensive experience in the palm oil industry in Malaysia.

3.2 Fuzzy Delphi Method

The FDM utilizes consensus among experts in the related field to support decision-making (Rowe & Wright 1999). This approach is based on an interval-value judgement: the minimum possible value (l1, l'1), the mean possible value (m2), and the maximum possible value (u'3, u3). The criteria values depend on linguistic preferences. Based on this, a large number of criteria are reduced to a limited number of more important ones that are hierarchically related to each other. The FDM is used to obtain a final decision through only one survey round. The FDM is becoming popular and has been tested as a way of helping managers solve real-life problems.

FIGURE 1 INSERTED HERE

3.3 Interpretive Structure Modeling

ISM is a combination of discrete mathematics, social science, graph theory and group discussion using computer assistance. It is a suitable modelling technique for analysing the influence of one criterion on another criterion, which helps to structure and guide a multi-faceted problem into a system. In addition, ISM is described as an interactive learning process in which a set of different and directly related criteria is structured into a comprehensive systematic model (Luthra & Mangla 2018). Thus, a model is created to portray a complex problem by using graphics as well as words. The proposed criteria are categorized by driving and dependence power into a hierarchical structural model. A relation matrix is formed by asking such questions as "Does feature e_i inflect feature e_j?" If the answer is "Yes", then $d_{ij} = 1$; otherwise, $d_{ij} = 0$. The general relation matrix, D, is thus formed. The relation matrix is constructed and the reachability matrix is calculated using Equations (1) and (2).

$$M = D + I \tag{1}$$

$$M^{*} = M^{k} = M^{k+1} \quad k > 1. \tag{2}$$

The reachability set and the priority set are calculated based on Equations (3) and (4) as the following equations.

$$A(t_i) = \{t_j \middle| m'_{ij} = 1\} \tag{3}$$

$$R(t_i) = \{t_j \middle| m'_{ij} = 1\} \tag{4}$$

where m_{ij} denotes the value of the ith row and the jth column.

Equation (5) shows that the levels of the elements and the relationships between them are determined, and the structure of the element relationships can also be expressed using the graph.

$$R(t_i) \cap A(t_i) = R(t_i)$$

(5)

3.4 Proposed analytical procedures

This study proposes a two-step methodology: (1) identifying challenges to I4.0 in CE through the FDM and (2) identifying the influential challenges using ISM. The challenges to I4.0 in CE is identify from the literature by following Daddi et al. (2018).This study focuses on articles mentioning ‘industry 4.0’ or ‘circular economy’ associated with the term ‘challenges’ or ‘barriers’ in title, abstracts and keywords. The results were then filtered by subject area, in order to source articles categorized as business, management and economics. The search was limited to specific timespan from 2015-2019. Articles were filtered by language, in order to include only international publications in English. Resulting articles were selected on the basis of references to ‘challenges to I4.0’ or ‘challenges to CE’ contained in titles and abstract. As a result, 30 out of 54 challenges to I4.0 in CE emerged as eligible for the analysis. Therefore, the number of articles dropped from the original 84 articles to 54 papers. The detailed FDM steps are described below.

1. A set of proposed challenges is collected from the literature review. Based on the detailed review, the identified challenges are shown in Table 1A in Appendix A.
2. The proposed challenges are developed, and 14 experts (decision-makers) included 4 experts from academia and 10 experts from the industry are invited to test the content validity through the questionnaire using the linguistic variables described in Table 1. This step is important for establishing a set of challenges for FDM evaluation.

TABLE 1 INSERTED HERE

3. The FDM is used to identify the important challenges through comparing the weight of each barrier with the threshold value, $\tilde{a}$. The value of $\tilde{a}$ represents the cut-off for all the challenges and is calculated by the average of the weight of all challenges, $\tilde{a}_j$. The screening principle is as follows: If $\tilde{a}_j \geq \tilde{a}$, then challenge t is selected, and if $\tilde{a}_j < \tilde{a}$, then challenge t is rejected.
4. Since $\tilde{a}_j$ and $\tilde{a}$ are a combined fuzzy set, they need to be transformed into a crisp value for comparison. The crisp values are composed into the weight matrices and then into a pairwise comparison matrix. This study uses a simple centre of gravity method to reduce the fuzziness of the fuzzy weight, and the definite value is obtained.
5. ISM is used to compose the hierarchical structure and the driving and dependence power of the criteria using Equations (1)-(5).

4. Results

This study identified thirty initial challenges to I4.0 in CE through the literature analysis and experts’ experience and judgement.

1. The initial set of challenges to I4.0 in CE is shown in Appendix Table 1A. The FDM summarization is shown in Appendix Table 1B, along with the weights and the threshold for screening out criteria.
2. The linguistic terms are transformed into corresponding triangular fuzzy numbers, as shown in Table 1. The FDM is applied to refine the important challenges with the threshold $\tilde{a}$ = 0.4493. Eighteen challenges are accepted and subsequently renamed, as shown in Table 2.
3. The criteria are ranked by importance, with the top five challenges being lack of automation system virtualization (C2), unclear economic benefits of digital investment (C18), lack of process design (C28), unstable connectivity among firms (C19) and

employment disruptions (C7). These criteria are then employed to provide implications for practice.

TABLE 2 INSERTED HERE

4. ISM transforms unclear models into visible, well-defined models for many purposes. The following steps are used to analyse the challenges affecting I4.0 in CE in the palm oil industry in Malaysia.
   - Identify the structural challenges in an inter-relations matrix: For this purpose, experts from the industry and academia are consulted to determine the nature of the contextual relationship among the challenges. To examine the challenges, a contextual relationship of the 'leads to' or 'affects' type must be chosen. This means that one challenge affects another challenge. On this basis, the contextual relationship between the identified challenges is developed. The contextual relationship for each pair of challenges, the existence of a connection between any two factors (p and q), and the associated direction of the relationship are investigated (Table 3). Four symbols are used to denote the direction of the relationship between two factors (p and q): (1) V for the relation from challenge p to challenge q (i.e., challenge p is affected by challenge q); (2) A for the relation from challenge q to challenge p (i.e., challenge q is affected by challenge p); (3) X for the relation in both directions (i.e., challenges p and q influence each other); and (4) O for no relation between the challenges (i.e., challenges p and q are dissimilar).

TABLE 3 INSERTED HERE

   - Transform and establish the challenges in a reachability matrix: An overall structure is extracted from the complex set of challenges, and the information in each entry of the linguistic preferences is transformed into 1 or 0 in the reachability matrix according to the following inter-relationship (p and q) rules: (1) If the (p, q) entry is V, then the (p, q) entry in the reachability matrix becomes 1 and the (q, p) entry becomes 0; (2) if the (p, q) entry is A, then the (p, q) entry in the matrix becomes 0 and the (q, p) entry becomes 1; (3) if the (p, q) entry is X, then the (p, q) entry in the matrix becomes 1 and the (q, p) entry also becomes 1; and (4) if the (p, q) entry is O, then the (p, q) entry in the matrix becomes 0 and the (q, p) entry also becomes 0. The initial reachability matrix for the challenges is established, as shown in Table 4.
   - Develop a hierarchy of challenges: The reachability set and antecedent sets are derived (see Table 5). The reachability set consists of the challenge itself and the other challenges that it may affect, whereas the antecedent set consists of the challenge itself and the other challenges that may affect it. The intersection of these sets is derived for all the challenges, and the levels of different challenges are determined. The challenges for which the reachability and the intersection sets are the same occupy the top level in the ISM hierarchy model. The top-level challenges are those that do not lead to other challenges above their own level in the hierarchy model. Once a top-level challenge is identified, it is removed from the hierarchy. The same process is repeated and continued until the level of each challenge is determined. These levels help in creating the diagraph and the ISM model presented in Figure 2.

TABLE 4 INSERTED HERE
TABLE 5 INSERTED HERE

- Develop the four-quadrant map: dependence-driving power analysis (DPPA) is utilized to identify the relation of the dependence and driving power of challenges to I4.0 in CE. The proposed challenges are plotted on a four-quadrant map according to the driving power levels on the vertical axis and the dependence power levels on the horizontal axis (see Figure 3). The four quadrants are labelled as follows: (1) autonomous cluster (Cluster I): weak driving and dependence power, meaning the challenge is disconnected and has almost a null effect (influenced/influencing) on the system.; (2) dependent cluster (Cluster II): weak driving power but strong dependence power, which significantly needs all the other challenges to diminish the effect of these challenges during I4.0 in CE implementation; (3) linkage cluster (Cluster III): strong driving and dependence power, meaning the challenge is generally unstable, as it may create a feedback effect on the system (others and itself); and (4) independent cluster (Cluster IV): strong driving but weak dependence power, making the challenge a key challenge.

FIGURE 2 INSERTED HERE
TABLE 6 INSERTED HERE

- A criterion with strong driving power is known as a key challenge that falls into the independent (Cluster II) or linkage (Cluster III) cluster. The driving power and dependence power of each challenge are shown in Table 6. More details of the final full ISM hierarchy model for the challenges are shown in Figure 2. The ISM hierarchy model reveals that lack of automation system virtualization (C1), lack of closed-loop control (C2), unstable connectivity among firms (C13), lack of process design (C16) and lack of internet coverage and IT facilities (C18) are significant challenges to I4.0 in CE and form the base of the ISM hierarchy model. These challenges are categorized as technical and process categories. Employment disruption, which represents the employment category, is a challenge on which the effectiveness of I4.0 in CE depends. This challenge appears at the top of the hierarchy model. Subsequently, the diagram of driving power vs. dependence power for the challenges is constructed, as shown in Figure 3. As an illustration, Table 6 shows that there are only two challenges in Quadrant II: lack of closed-loop control (C2) and unclear economic benefits of digital investment (C12). Quadrant IV consists of three challenges: lack of standardization (C4), high investment (C8) and lack of leader experience (C14), which have strong driving power but weak dependence power. The remaining challenges are positioned according to their driving and dependence power based on Table 6.

FIGURE 3 INSERTED HERE

5. Implications

This study provides theoretical and managerial understanding and knowledge by determining the criteria that challenge the implementation of I4.0 in CE in order to balance the social impacts, reduce the environmental risks and increase the economic benefits in palm oil industry. Few studies have empirically demonstrated such relationships for I4.0 in CE; thus, this is an original contribution of our work, and this study fills a gap in the literature. This section discusses the theoretical and managerial implications followed by limitations and suggestions for future study

5.1 Theoretical implications

The results provide insight into the relative importance of these challenges and the interdependencies between them. The findings of this study highlight seven autonomous challenges in Quadrant I: employment disruption (C5), lack of understanding of I4.0 implications (C6), financial constraints (C7), low management support and dedication (C10), poor company digital operation mission and vision (C11), unstable connectivity among firms (C13) and lack of internet coverage and IT facilities (C18). These challenges however, do not have much influence on the palm oil industry system, and they are considered not to be significant challenges to I4.0 in CE.

Dependent clusters (Quadrant II) are lack of closed-loop control (C2) and unclear economic benefits of digital investment (C12). These challenges are weak drivers but are strongly dependent on one another. Due to the lack of a clear definition of return on investment and an unknown level of economic benefits, many firms especially palm oil are afraid and hesitant to invest. For these reasons, there is substantial risk since these firms require a tremendous upfront investment, and market validation causes the slow uptake of technology in I4.0 in CE. The future of a firm may be jeopardized by a doomed investment, and in extreme conditions, high investment is often significantly risky and challenging. These slow-downs may eventually result in business failure (Ghobakhloo & Ching 2019). Firms need to understand that achieving economic benefits in a short time is not easy or predictable, and time is needed to recoup the investment (Kinnunen & Kaksonen 2019; Luthra & Mangla 2018b). Effective economic benefits are required to boost assurance, and this is achieved only when academic theory interacts effectively with practice. When palm oil industry is aiming to increase the economic benefits, developing a clear picture of economic benefits is necessary, and technically and legally beneficial low-cost technology to ensure an effective and efficient production process that is acceptable to firms is urgently required.

The linkage cluster that cause poor palm oil industry performance (Quadrant III) consists of six challenges: lack of automation system virtualization (C1), lack of legacy IT infrastructure (C3), lack of collaborative I4.0 model (C9), lack of organizational and process design (C15), lack of process design (C16) and lack of knowledge management system (C17). Two of these challenges are from the technical and process categories, and four of them are from the collaborative management category in the ISM hierarchy model. These challenges are significant criteria to palm oil industry that have strong driving power and strong dependence power, challenging I4.0 in CE. However, these challenges are unstable, which means that any action related to one of them has an effect on other challenges and feeds back on it as well. This study proved that palm oil industry failed to communicate with each other to develop business relationships due to inconsistent collaboration among them in the supply chain (Fischer & Pascucci 2017). Thus, it is important for palm oil industry to plan internal transitions towards I4.0 in CE as well as external transitions along the chain. In addition, machines may not be connected to a good network or may break down because of unexpected situations, such as power outages, or data may be missing from a machine log. The data analytics module needs to integrate discrete data logs and interpret missing data based on adjacent data and defined business rules. Real-time data for the IoT are critical, as they are used for critical operations to detect malfunctions, predict maintenance needs, increase production, reduce downtime and detect anomalies. Based on these reasons, a stable legacy IT infrastructure among firms in palm oil industry should be developed, as the current approach is not applicable. The network connection must be stable to ensure that the production process between firms along the supply chain is successful.

The independent cluster (Quadrant IV), which has strong driving power but weak dependence power, consists of three challenges: lack of standardization (C4), high investment (C8) and lack of leader experience (C14). These challenges are known as key challenges which causes poor performance to palm oil industry, as they demand the greatest attention from academics and practitioners. Hence, palm oil industry need to overcome these challenges in order to successfully implement I4.0 in CE. Several scholars have noted that a low degree of standardization may occur inter-organizationally, and this problem could hinder I4.0 in CE adoption (Müller & Voigt 2016; Nagy 2019). In addition, I4.0 in CE also requires significant financial resources, which may hinder firms from investing (Horváth and Szabó 2019). This was confirmed by Ghobakhloo and Ching (2019), who stated that technology innovation demands higher investment, as many tests need to be conducted to ensure that new production approaches are successfully implemented. Successful I4.0 in CE requires a wide range of skills in modern technologies in order to achieve a higher level of productivity, which depends largely on the cyber-physical network. Therefore, firms in palm oil industry should take the initiative to improve leader experience by sending leaders for training, such as a short course to gain knowledge of current technology innovations. This practice benefits the firm in the long term.

5.2 Managerial implications

The six most influential challenges with the highest driving power that causes poor performace in palm oil industry are lack of organizational and process changes (C15), lack of closed-loop control (C2), lack of internet coverage and IT facilities (C18), lack of automation system virtualization (C1), lack of process design (C16) and lack of knowledge management system (C17). The six most influential challenges with the highest dependence power in the context of palm oil industry are lack of process design (C16), lack of automation system virtualization (C1), high investment (C8), lack of collaborative I4.0 model (C9), lack of knowledge management (C17) and lack of legacy IT infrastructure (C3). Lack of process design (C16), lack of automation system virtualization (C1) and lack of knowledge management system (C17) are the common intersecting challenges that have the highest driving power and dependence power. Interestingly, all three of these challenges are in Quadrant III (linkage cluster); two of them are in Level 5, which is known as the technical and process category, and the third is in the collaborative management category. It may be noted that not much literature is available in the focused domain for challenges to I4.0 in CE, specifically in the agriculture industry. Thus, results from previous studies of various industries have been compared with the findings of this study.

In the technical and process category, lack of process design (C16) is the greatest challenge that can hinder the implementation and development of I4.0 in CE in palm oil industry, with a driving power of 13 and a dependence power of 17. This study supports the claim that poor strategy design and process with limited creation of indicators of performance hinder implementing I4.0 in CE (Elia et al. 2017; Ngan et al. 2019). Hence, successful I4.0 in CE requires a process design that maintains the integrity of production processes (Sung 2018). To achieve sustainability, palm oil stakeholders in I4.0 in CE should plan and act on future data analytics strategies to expedite machine learning and artificial intelligence applications in order to maintain their competitive and innovative environment (Gürdür et al. 2019). Such revolutionary transformations may improve I4.0 in CE; thus, palm oil industry must develop the optimal process design strategies. This is possible only by ensuring the involvement of management from firms and industries to provide business actions with concrete plans. This further helps process design and practice managers in palm oil industry to implement technology more effectively. With the promotion of training activities and an emphasis on learning and fostering knowledge, there is an urgent need to improve I4.0 in CE process design to meet current and future work requirements in the context of palm oil industry. Focusing on the understanding of the process design of I4.0 in CE, practitioners and managers should build the optimal design model that minimizes the risk of cyber-physical systems.

Moreover, the lack of automation system virtualization (C1), with a driving power of 13 and a dependence power of 16, is the most significant challenge that needs attention from palm oil practitioners. These hurdles exist because the understanding of system virtualization is still in the early stage, and the physical processes monitored by cyber-physical systems for simulation and virtual plant models are less ubiquitous than others (Frank et al. 2019). Furthermore, the scarcity of guidelines and standards makes it challenging for palm oil firms to implement I4.0 in CE, which creates difficulties in reducing production waste and monitoring operational and production processes (Govindan & Hasanagic 2018; Ngan et al. 2019). Increased reliability of connectivity between machines and integrity of maintenance-related data and available information create more virtualization problems that are challenging to manage, and the implementation of I4.0 in CE therefore remains low and slow (Sung 2018). In this sense, insight into I4.0 in CE must be synchronized in palm oil industry to reduce production waste and monitor the operational and production processes. There is a need for firms, together with the palm oil industry, to develop an efficient and effective automation system virtualization to be implemented in the production process. Palm oil practitioners and managers should design an innovative technology system that increases and maximizes the real-time visibility of operational processes, thus offering reliable and efficient solutions.

In the collaborative management category, the lack of knowledge management system (C17) is confirmed as a vast challenge to palm oil industry, with a driving power of 13 and a dependence power of 13, particularly when knowledge management is directly related to the decision-making process from a strategic perspective. As such, I4.0 in CE refers to technology to increase the amount of available data and to allow the transformation of data into knowledge that is used by practitioners. Moreover, this process can also help to improve a firm overall by making it competitive in the long term (Dalmarco et al. 2019; Winans et al. 2017). In addition, knowledge of how to transform the firm's current operations into I4.0 in CE may be lacking, which hinders adoption in palm oil industry. To address these challenges, exchanging knowledge management by connecting information and creating value through networks can increase knowledge sharing (Tura et al. 2019). For that reason, training activities and knowledge management improvement for high-skilled workers are urgently needed by firms and the palm oil industry. This training and knowledge are crucial in managing the negative impacts of I4.0 in CE. Despite the technological requirements inherent to self-sufficient production processes, the demand for specific skills, meaning high-skilled workers, may have an impact on the knowledge management system and palm oil operations. Thus, managers and firms in palm oil industry should improve the business environment and worker functions to generate prosperity and improve the quality of social life.

Overall, the major challenges to I4.0 in CE in the context of palm oil industry are lack of automation system virtualization, lack of process design and lack of knowledge management system. There are other challenges that have led to the current failure to implement I4.0 in CE: lack of standardization, financial constraints, high investment, lack of leader experience and lack of internet coverage and IT facilities. Hence, Sung (2018) suggested four improvements to move towards I4.0 in CE: government should (1) refine and elaborate strategies and plans to build economic and social systems that are flexible to respond to change, (2) establish a production system that maximizes the effectiveness of the policies and initiatives, (3) develop concrete action plans that can accommodate changes in a turbulent environment and economy with an unbalanced social structure and (4) establish infrastructure to lead all initiatives with specific standards that collaborate with stakeholders. In practice, firm managers identified challenges in focusing not only on front-end technologies but also on the base technologies that provide support for the implementation of I4.0 in CE.

5.3 Limitation and future directions

This study has several limitations, and there is a wide range of opportunities for future study in this area. First, this study limited the criteria to thirty challenges, and future studies should elaborate on these and be extended to more relevant challenges. As the development of I4.0 in CE is in its infancy, there is little understanding of how I4.0 in CE operates and the associated benefits. Second, this study was conducted in Malaysia, specifically in the palm oil industry, and findings from other countries and industries may present different challenges. This study should be extended to other countries and industries. The results from this study should also be compared to the findings of future studies to develop a better understanding of the issues. Third, this study applied the FDM to screen out attributes and ISM to identify influential challenges; however, these methods have weaknesses. The opinion of the experts may be biased, and ISM fails to distinguish between cause and effect factors. Future studies are recommended to perform technical validity evaluations.

6. Conclusions

I4.0 in CE has been a controversial topic in recent years; however, its implementation has become more complicated and has driven challenges that prevent firms from realizing social impacts, reducing environmental risks and increasing economic benefits. Thus, this study combined the insight from the previous literature on I4.0 and CE with the results of an empirical case study to develop challenges to I4.0 in CE, specifically in the palm oil industry in Malaysia. A set of 30 challenges is proposed and analysed using the FDM. Fuzzy set theory is applied to convert the attributes identified by experts into measurable data. The Delphi method is adopted to remove unnecessary attributes and rank the remaining attributes according to their priority. Hence, this study weighs experts' linguistic judgement to produce valid and reliable results with both theoretical and practical implications. Overall, this study identifies the challenges to I4.0 in CE by determining the major attributes causing barriers to reducing production waste and monitoring the operational and production processes. The findings show that eighteen challenges to I4.0 in CE are accepted, and ISM is used to compose the hierarchical structure for practice. In particular, the main challenges to I4.0 in CE with strong driving power and strong dependence power are lack of automation system virtualization, lack of process design and lack of knowledge management system. These challenges play an important role in bridging I4.0 in CE in the production process, which involves technology innovation.

This study theorizes that when more technology innovation is used to reduce production waste and monitor the operations and production processes – with the use of advanced and complicated technologies in I4.0 in CE – social, environmental and economic challenges are more likely to appear. Therefore, this study is important for managers since there are still unclear mechanisms and much uncertainty about I4.0 in CE, especially regarding technology innovation and cost benefit. Thus, managers need to pay much more attention to the challenges identified in this study to reduce cost management and induce symbiotic relationships in the firm. In addition, this study reveals a key opportunity that would enhance the potential for new business development by promoting clean technology innovation and especially helping firms to understand and manage the actual challenges. This study also indicates that the government, together with academics and the industry, must work to develop a concrete action plan that would benefit industry from the social, environmental and economic perspectives. The creation of policy for I4.0 in CE would be a great step towards the revolution.

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Appendix

Appendix Table 1A. List of proposed challenges of Industry 4.0 in Circular Economy

No	Proposed Challenges	Descriptions	Reference
C1	Lack of security and privacy issues	There is a huge amount of information flow that occurs on the Industry 4.0 platform posing cybersecurity threat and data privacy issues. Virtual work on servers or platforms obligates employees to be aware of cyber security.	Alaba et al. (2017); Pereira et al. (2017); Yu et al. (2017); Horváth & Szabó (2019)
C2	Lack of automation system virtualization	It maximizes the real-time visibility of the operation processes which offers reliable and efficient solutions.	Babiceanu & Seker (2016); Schumacher et al. (2016)
C3	Lack of closed-loop control	The link between analytics and actuation must be closed so that a truly intelligent closed-loop control strategy is implemented in the next generation of intelligent manufacturing.	Chen (2017)
C4	Lack of knowledge base	The availability of an effective knowledge base is still the bottle-neck in the implementation of intelligent manufacturing technology.	Chen (2017); Ras et al. (2017); Schuh et al. (2017)
C5	Lack of legacy IT infrastructure	Legacy IT infrastructure must be re-evaluated or replaced for the new manufacturing paradigm.	Chen (2017); Leitao et al. (2016); Bedekar (2017); Pfohl et al. (2017)
C6	Lack of standardization	Necessary in order to integrate different elements in manufacturing systems, including both hardware and software.	Chen (2017); Branke et al. (2016); Leitao et al. (2016)
C7	Employment disruptions	The disruptions brought in the employment due to the emerging technologies and automation and resulting in human job losses.	Frey & Osborne (2017); Erol et al. (2016); Ras et al. (2017); ; Horváth & Szabó (2019)
C8	Lack of understanding on Industry 4.0 implications	There is very low understanding on Industry 4.0 implications among both the researchers and practitioners. Demands highly organized and focal study for a specific definition of the Industry 4.0.	Almada-Lobo (2016); Hofmann & Rusch (2017); Horváth & Szabó (2019)
C9	Data insecurity of Industry 4.0	Lack of systems to ensure enough data protection for the manufacturing companies during the implementation of Industry 4.0.	Horváth & Szabó (2019); Gölzer et al. (2015); Zhou et al. (2016)
C10	Financial constraints	A very important challenge among business organizations for developing their capabilities in terms of advanced equipment and machines, facilities and sustainable process innovations.	Theorin et al. (2017); Nicoletti (2018); Horváth & Szabó (2019)
C11	High investment	Industry 4.0 initiatives in the manufacturing industry require huge capital investment.	Zhou et al. (2016); Koch et al. (2014); Horváth & Szabó (2019)
C12	Lack of capabilities to reconfiguring of production pattern	Lack of capabilities to reconfigure the production pattern for the successful implementation of Industry 4.0 in the manufacturing companies.	Horváth & Szabó (2019); Khan et al. (2017); Saucedo-Martinez et al. (2017)
C13	Lack of collaborative Industry 4.0 model	It is required for direct interaction with the humans and also designed robots offers safety work to the humans within a defined workspace.	Tan et al. (2009); Horváth & Szabó (2019)
C14	Lack of data analysis	As large amount of data gets capture in different formats, analysing data and making informed decisions using analytics.	Horváth & Szabó (2019); Santos et al. (2017)
C15	Lack of global standards and data sharing protocols	In Industry 4.0 initiatives, systems generally coupled to an intelligence mechanism to communicate freely. To achieve success in this, industries need to follow global standards and data sharing protocols. It has been notices that industries lacks in standards and protocols in data transfers in adopting sustainability oriented modern information interfere technologies in business networks.	Horváth & Szabó (2019); Schroder (2016); Muller et al. (2017); Lin (2016); Claudia (2015)

No	Proposed Challenges	Descriptions	Reference
C16	Low management support and dedication	The most relevant management practices should be established organizations should focus on improving their capabilities in terms of employee training and development, knowledge management programs, for Industry 4.0 driven sustainable business development.	Horváth & Szabó (2019); Gokalp et al. (2017); Savtschenko et al. (2017); Shamim et al. (2017); Muller et al. (2017); Theorin et al. (2017); Perales et al. (2018)
C17	Poor company digital operations vision and mission	Organizations seem to struggle when transforming the visionary ideas of Industry 4.0 to a missionary level of developing the sustainability of supply chains.	Horváth & Szabó (2019); Erol et al. (2016)
C18	Unclear economic benefit of digital investments	The lack of defined return on investment could be seen as a one of major challenges to Industry 4.0 initiatives for accomplishing sustainability in the supply chain.	Kiel et al. (2017); Marques et al. (2017); Horváth & Szabó (2019)
C19	Unstable connectivity among companies	Insecure connectivity impairs real time communication among manufacturing companies challenging the implementation of Industry 4.0	Horváth & Szabó (2019); Duarte & Cruz-Machado (2017); Pfohl et al. (2017); Deloitte (2015); Khan et al. (2017); Zhou et al. (2016)
C20	Lack of experience leader	As production processes are digitized, companies need a leader with the necessary skills and experience to control Industry 4.0 projects	Horváth & Szabó (2019)
C21	Lack of integration of technology platforms	The integration of technologies is very essential in effective communication and higher productivity. Industries are facing difficulties in designing a flexible interface to integrate various heterogeneous components.	Zhou et al. (2015); Horváth & Szabó (2019)
C22	Lack of organizational and process changes	Organization functions may change owing to automation Industry 4.0 rise to decentralized organizations. Decision making lies at the shop floor level.	Broring et al. (2017); Hussain (2017); Valmohammadi (2016); Horváth & Szabó (2019)
C23	Lack of skills and qualifications	The skills and qualifications of the workforce becomes the key to success of a highly innovative factory which require a lot of prerequisite knowledge which cuts across various technical and non- technical disciplines.	Benesova & Tupa (2017); Peter et al. (2017); Hung (2016); Horváth & Szabó (2019)
C24	Lack of technological infrastructure	Nonexistence of technological infrastructure to support the manufacturing companies implementation of Industry 4.0	Zhou et al. (2016); Waibel et al. (2017); Horváth & Szabó (2019)
C25	Lack of compatibility	It keeps the system's components working together in a functioning environment without implementing any changes to the system.	Leitao et al. (2016); Schutze et al. (2018); Hussain (2017); Valmohammadi (2016); Buntz (2017)
C26	Lack of infrastructure and internet based networks	High infrastructure, information technology based facilities and technologies are crucial in effective adoption of Industry 4.0 concepts. Poor internet connectivity is an imperative barrier to Industry 4.0 initiatives.	Leitao et al. (2016); Elkhodr et al. (2016)
C27	Lack of infrastructure standardisation	Infrastructure is required to equip the advance technologies. It is required to integrate the heterogeneous devices/components in automation systems.	Leitao et al. (2016); Mueller et al. (2017); Haddud et al. (2017); Li et al. (2016)
C28	Lack of process design	Design the process model and to include cyber-physical systems-enabled landscapes.	Leitao et al. (2016); Posada et al. (2015); Shellshear, Berlin & Carlson (2015)

No	Proposed Challenges	Descriptions	Reference
C29	Lack of knowledge management systems	Information technology systems that store and retrieve knowledge, improve collaboration, locate knowledge sources, mine repositories for hidden knowledge, capture and use knowledge and enhance the knowledge management process.	Lorna & He (2017); Rymaszewska et al. (2017)
C30	Lack of internet coverage and IT facilities	Lack solutions for effective communication and signal coverage may act as a significant blockade for various products/ services. Signal attenuation occurs due to weak signal coverage in certain manufacturing premises.	Fang et al. (2016); Yan et al. (2014a); Yan et al. (2014b)

Appendix Table 1B. FDM list - 30 challenges of I4.0 in CE screening out

Challenges	l_b	u_b	D_b	Decision
C1	0.0000	0.5000	0.3333	Unaccepted
C2	0.1130	0.7620	0.5913	Accepted
C3	(0.2417)	0.7417	0.4945	Accepted
C4	0.0000	0.5000	0.3333	Unaccepted
C5	(0.1958)	0.6958	0.4639	Accepted
C6	0.1466	0.7284	0.5689	Accepted
C7	0.1372	0.7378	0.5752	Accepted
C8	(0.2773)	0.7773	0.5182	Accepted
C9	0.0000	0.5000	0.3333	Unaccepted
C10	(0.2300)	0.7300	0.4867	Accepted
C11	(0.2683)	0.7683	0.5122	Accepted
C12	0.0000	0.5000	0.3333	Unaccepted
C13	0.1628	0.7122	0.5582	Accepted
C14	0.0000	0.5000	0.3333	Unaccepted
C15	0.0000	0.5000	0.3333	Unaccepted
C16	(0.1748)	0.6748	0.4499	Accepted
C17	(0.2122)	0.7122	0.4748	Accepted
C18	0.1173	0.7577	0.5885	Accepted
C19	0.1275	0.7475	0.5817	Accepted
C20	(0.2122)	0.7122	0.4748	Accepted
C21	0.0000	0.5000	0.3333	Unaccepted
C22	(0.1991)	0.6991	0.4660	Accepted
C23	0.0000	0.5000	0.3333	Unaccepted
C24	0.0000	0.5000	0.3333	Unaccepted
C25	0.0000	0.5000	0.3333	Unaccepted
C26	0.0000	0.5000	0.3333	Unaccepted
C27	(0.1586)	0.6586	0.3333	Unaccepted
C28	0.1234	0.7516	0.5844	Accepted
C29	(0.1912)	0.6912	0.4608	Accepted
C30	(0.2840)	0.7840	0.5226	Accepted
Threshold			**0.4493**	

***Highlights (for review)**

Highlights

- This study proposes a model to understand the challenges to Industry 4.0 in circular economy to obtain social, economic and environmental benefits in practice
- Fuzzy Delphi Method is to screen out the less-important attributes.
- Interpretive structural modelling is to interpret the interrelationships among the challenges in practices
- This study contributes to unveiling what challenges Industry 4.0 in circular economy faces for operational decision-making

Figure(s)

Figures

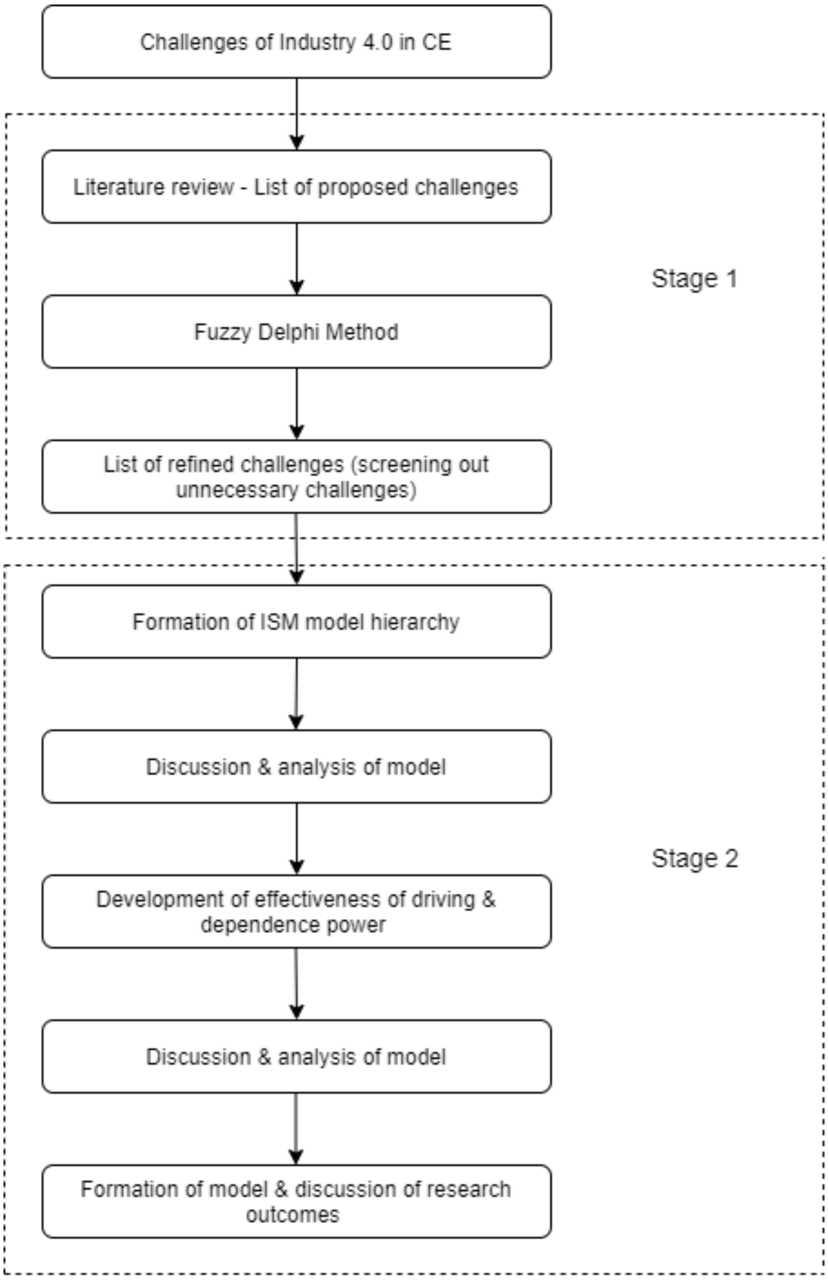

Figure 1 Proposed research work flowchart

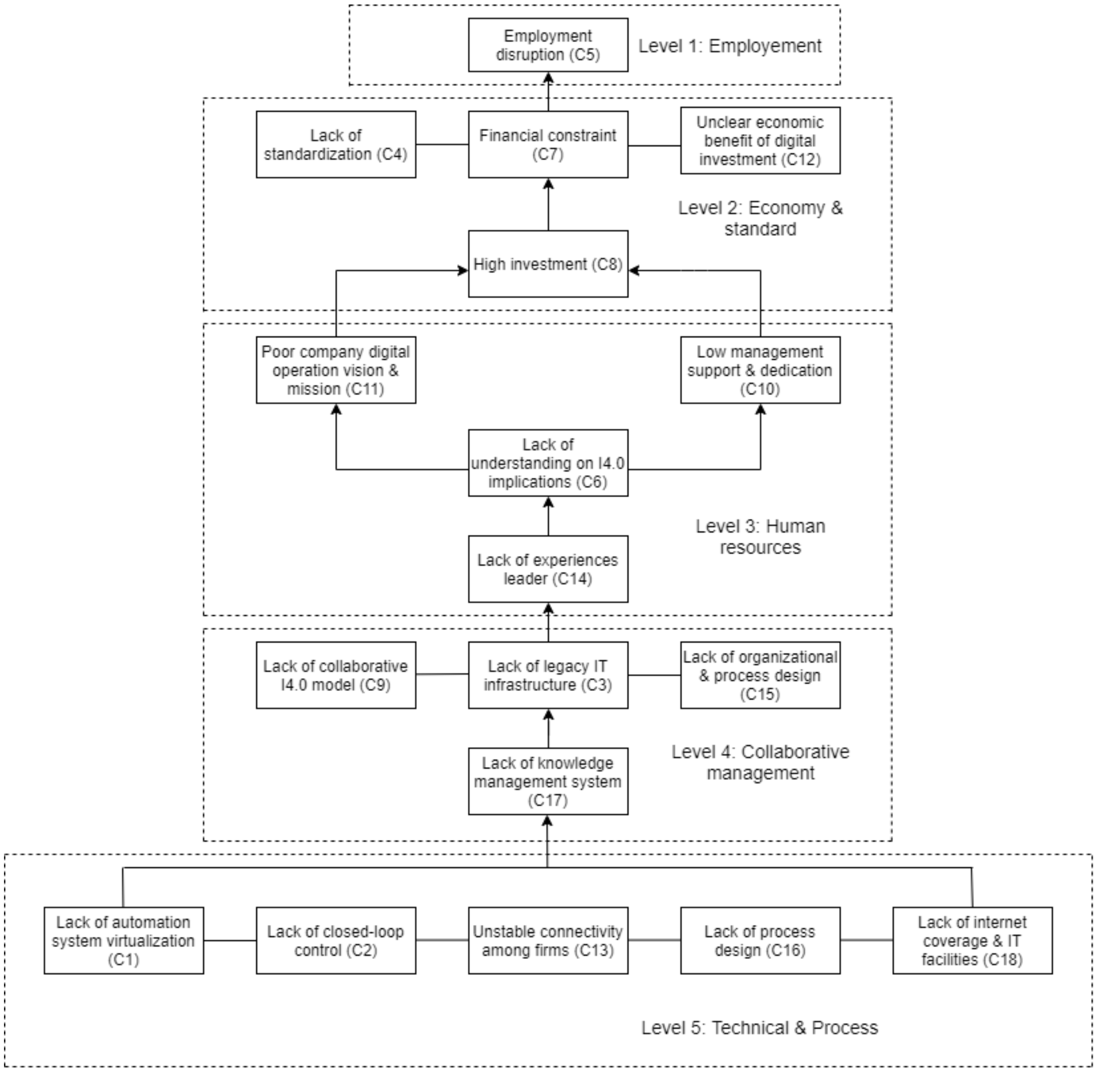

Figure 2 ISM for challenges

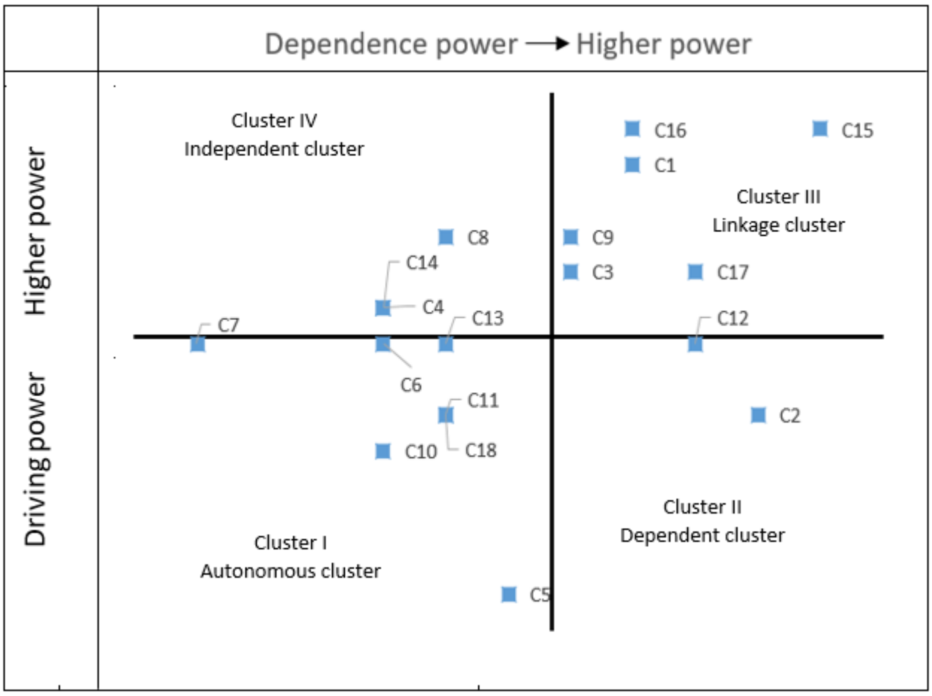

Figure 3 Clusters of challenges I4.0 in CE

Table(s)

Tables

Table 1. Transformation table of linguistic terms.

Linguistic terms (performance/ importance)	Corresponding triangular fuzzy number
Extremely	(0.75, 1.00, 1.00)
Demonstrated	(0.50, 0.75, 1.00)
Strong	(0.25, 0.50, 0.75)
Moderate	(0.00, 0.25, 0.50)
Equal	(0.00, 0.00, 0.25)

Table 2. List of FDM- challenges results.

Renamed	Challenges	Ranking
C1	Lack of automation system virtualization	1
C2	Lack of closed-loop control	11
C3	Lack of legacy IT infrastructure	16
C4	Lack of standardization	6
C5	Employment disruptions	5
C6	Lack of understanding on Industry 4.0 implications	9
C7	Financial constraints	12
C8	High investment	10
C9	Lack of collaborative Industry 4.0 model	7
C10	Low management support and dedication	18
C11	Poor company digital operations vision and mission	13
C12	Unclear economic benefit of digital investments	2
C13	Unstable connectivity among firms	4
C14	Lack of experience leader	14
C15	Lack of organizational and process changes	15
C16	Lack of process design	3
C17	Lack of knowledge management systems	17
C18	Lack of internet coverage and IT facilities	8

Table 3. Structural challenges inter-relations matrix

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17
C18	X	X	X	V	O	O	O	A	X	O	O	O	X	O	X	X	A
C17	X	X	A	V	X	X	O	A	X	X	X	A	A	V	X	X	-
C16	X	X	X	X	V	V	V	V	X	X	X	X	X	O	X	-	
C15	X	V	V	X	X	A	A	A	X	X	X	A	A	A	-		
C14	X	X	X	O	O	X	O	V	X	X	X	V	O	-			
C13	X	X	X	A	O	O	O	V	X	O	A	X	-				
C12	A	A	A	A	X	A	X	X	V	A	A	-					
C11	A	O	A	A	O	X	O	A	O	O	-						
C10	O	V	O	A	O	X	A	A	O	-							
C9	A	V	V	X	V	X	X	V	-								
C8	X	V	X	V	V	X	X	-									
C7	V	V	X	V	V	O	-										
C6	X	V	O	O	O	-											
C5	A	O	A	A	-												
C4	X	V	V	-													
C3	X	X	-														
C2	X	-															
C1	-																

Table 4. Initial reachability matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
C1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1
C2	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1
C3	1	1	1	1	0	0	1	1	1	0	0	0	1	1	1	1	0	1
C4	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1
C5	1	0	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	0
C6	1	0	0	0	0	1	0	1	1	1	1	0	0	1	0	1	1	0
C7	0	0	1	0	0	0	1	1	1	0	0	1	0	0	0	1	0	0
C8	1	0	1	0	0	1	1	1	1	0	0	1	1	1	0	1	0	0
C9	1	0	0	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1
C10	0	0	0	1	0	1	1	1	0	1	0	0	0	1	1	1	1	0
C11	1	0	1	1	0	1	0	1	0	0	1	0	0	1	1	1	1	0
C12	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	0
C13	1	1	1	1	0	0	0	0	1	0	1	1	1	0	0	1	0	1
C14	1	1	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1	0
C15	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
C16	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	1	1	1
C17	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	0
C18	1	1	1	0	0	0	0	1	1	0	0	0	1	0	1	1	1	1

Table 5. Level of challenges I4.0 in CE

Challenges	Reachability	Antecedent	Intersection	Level
C1	2,3,4,6,7,8,13,14,15,16,17,18	2,3,4,6,8,13,14,15,16,17,18	2,3,4,6,8,13,14,15,16,17,18	IX
C2	1,3,4,6,7,8,9,10,13,14,15,16,17,18	1,3,13,14,16,17,18	1,3,13,14,16,17,18	IX
C3	1,2,4,7,8,9,13,14,15,16,18	1,2,7,8,13,14,16,18	1,2,7,8,13,14,16,18	VII
C4	1,7,8,9,15,16,17,18	1,9,15,16	1,9,15,16	II
C5	1,3,4,7,8,9,12,15,16,17	12,15,17	12,15,17	I
C6	1,8,9,10,11,14,16,17	1,8,9,10,11,14,17	1,8,9,10,11,14,17	V
C7	3,6,8,9,12,16	3,8,9,12	3,8,9,12	II
C8	1,3,6,7,9,12,13,14,16	1,3,6,7,12	1,3,6,7,12	III
C9	1,4,6,7,12,13,14,15,16,17,18	4,6,13,14,15,16,17,18	4,6,13,14,15,16,17,18	VII
C10	4,6,7,8,14,15,16,17	6,14,15,16,17	6,14,15,16,17	IV
C11	1,3,4,6,8,14,15,16,17	6,14,15,16,17	6,14,15,16,17	IV
C12	1,2,3,4,5,6,7,8,10,11,13,14,16	5,7,8,13,16	5,7,8,13,16	II
C13	1,2,3,4,9,11,12,16,18	1,2,3,9,12,16,18	1,2,3,9,12,16,18	IX
C14	1,2,3,6,9,10,11,17	1,2,3,6,9,10,11	1,2,3,6,9,10,11	VI
C15	1,4,5,6,7,8,9,10,11,12,13,14,16,17,18	1,4,5,9,10,11,16,17,18	1,4,5,9,10,11,16,17,18	VII
C16	1,2,3,4,9,10,11,12,13,15,17,18	1,2,3,4,9,10,11,12,13,15,17,18	1,2,3,4,9,10,11,12,13,15,17,18	IX
C17	1,2,3,5,6,8,9,10,11,12,13,15,16	1,2,5,6,9,10,11,15,16	1,2,5,6,9,10,11,15,16	IX
C18	1,2,3,8,9,13,15,16,17	1,2,3,9,13,15,16	1,2,3,9,13,15,16	VIII

Table 6

Driving and dependence power in reachability matrix

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	**C16**	C17	C18	Driving power
C1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	**1**	1	1	13
C2	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	**1**	1	1	15
C3	1	1	1	1	0	0	1	1	1	0	0	0	1	1	1	**1**	0	1	12
C4	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	**1**	1	1	9
C5	1	0	1	1	1	0	1	1	1	0	0	1	0	0	1	**1**	1	0	11
C6	1	0	0	0	0	1	0	1	1	1	1	0	0	1	0	**1**	1	0	9
C7	0	0	1	0	0	0	1	1	1	0	0	1	0	0	0	**1**	0	0	6
C8	1	0	1	0	0	1	1	1	1	0	0	1	1	1	0	**1**	0	0	10
C9	1	0	0	1	0	1	1	0	1	0	0	1	1	1	1	**1**	1	1	12
C10	0	0	0	1	0	1	1	1	0	1	0	0	0	1	1	**1**	1	0	9
C11	1	0	1	1	0	1	0	1	0	0	1	0	0	1	1	**1**	1	0	10
C12	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	**1**	0	0	14
C13	1	1	1	1	0	0	0	0	1	0	1	1	1	0	0	**1**	0	1	10
C14	1	1	1	0	0	1	0	0	1	1	1	0	0	1	0	**0**	1	0	9
C15	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**16**
C16	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	**1**	1	1	13
C17	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	**1**	1	0	13
C18	1	1	1	0	0	0	0	1	1	0	0	0	1	0	1	**1**	1	1	15
Dependence power	16	9	13	12	4	11	11	14	14	8	8	9	11	11	12	**17**	13	9	

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