The future of industry 4.0 and the circular economy in Chinese supply chain: In the Era of post-COVID-19 pandemic

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Abstract

The demand for new productive factors is increasingly required, exacerbated in a scenario in which a linear economy prevails. The circular economy (CE) adoption is a proposal to guarantee environmental sustainability and redirect an obsolete process such as the linear economy. Thus, one of the main factors that allow achieving sustainability is Industry 4.0 (I4.0). In addition, the research aims to evaluate the role of I4.0 during the COVID-19 pandemic in China. The literature review process defines ten future projections with potential for the CE's adoption. The two-round Delphi approach was developed with 54 CE experts to evaluate the projections. In both rounds, the probability of occurrence up to 2030, its impact on the CE and its desirability were evaluated. Likewise, the qualitative criteria of the experts were coded to evaluate the projections. From the ten projections, four are those with the highest probability of occurrence (EP > 70%), with high impact (I > 3.5) and desirability of occurrence (I > 3.5). Expert evaluations make it possible to identify that Industry 4.0 and the digital skills of workers, their financing, and the efficiency of Government policies have a high probability of occurrence in the adoption of the CE in 2030. This research responds to the special call of papers providing evidence favouring the implementation of I4.0 in the CE from a holistic approach to draw a roadmap towards adopting the CE practices.

Keywords Circular economy · Industry 4.0 · COVID-19 · Delphi approach · Environmental policies · Supply chain management

1 Introduction

The demand for productive factors worldwide is growing more and more, and it faces a scarcity scenario, becoming the main problem of maintaining a production system based on a linear economy (Guerra and Leite 2021a). The linearity of the economy in the production process causes the global supply chain of products to be less resilient and suffer continuous failures in its operation that affect the balance of the markets (Manavalan and Jayakrishna 2019; Yu and Khan 2021). That is why the circular economy (CE) approach constitutes a challenge to counteract the growing scarcity of productive resources, favouring the conservation of the environment (Manavalan and Jayakrishna 2019). The adoption of a CE favours two aspects specifically. First, a production system under the CE approach benefits business

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performance and clean production (Khan et al. 2021a); secondly, the firm improves its efficiency, thereby improving its integration into the sector's supply chain to which it belongs (El Wali et al. 2021). This situation also generates externalities for all agents in the supply chain since the improvement of the supply chain generates benefits over other firms that comprise it (Khan and Qianli 2017).

Thus, one of the main elements to consider when approaching the CE implementation is a technological innovation in production processes since state-of-the-art technology is required to process waste and ecological designs (Kumar et al. 2021). Recent studies show evidence in favour of the implementation of emerging technologies of Industry 4.0 (I4.0), such as blockchain technology (Upadhyay et al. 2021), artificial intelligence (Kumar et al. 2020), or cloud computing, internet of things (IoT), smart objects, GPS, among others (Bag et al. 2020), on the CE. All the I4.0 contribute to improving the firm's performance and implementing sustainable production practices, consequently improving the firm's integration and coordination in the supply chain (Perdana et al. 2020).

Similarly, a factor that is relevant in the adoption of CE is the Corona Virus Disease 2019 (COVID-19) outbreak, which has had severe implications for the performance of firms (Pan et al. 2021) and consequently in supply chains (Meléndez et al. 2020). COVID-19 has become an opportunity and a threat for firms since, in some cases, it has been a mandatory determinant to accelerate the transition from a linear to a CE (Meléndez et al. 2020) and, in other scenarios, has been an obstacle to adopt more efficient production systems and environmental improvement (Parashar and Hait 2021). As mentioned above, an opportunity is constituted because some firms have invested in technological solutions to reopen or maintain operations; and in others, it has become unsustainable due to the increase in single-use products that generate more waste. Additionally, COVID-19 was an eventuality that directly affected the economic and environmental performance of the firm; however, the firms that managed to remain in the market were those that had a more developed state of technology, which allowed them to improve their resilience and adapt to the inefficiency of the supply chain affected by the pandemic (Christiaensen et al. 2020).

However, there are some other barriers and enablers for adopting the CE to the factors mentioned above. The previous literature has defined that adopting the CE must consider financing to transform production processes (Millette et al. 2020). Public concern for more environmentally friendly production processes (Liu and Bai 2014) and, in addition, environmental Government regulations, which must be appropriately addressed so that they become support in the process of transition to a CE.

Although there is evidence favouring the benefits of I4.0 over CE in developed economies in which they have a highly developed technological, economic, political and institutional level, the empirical evidence in developing countries during COVID-19 is limited (Bag et al. 2021). In this context, this research focuses on China because, in 2015, the Chinese Government raised the project called "Made in China 2025" (Yang et al. 2020). This project aims to promote the CE and the use of resources (Chen et al. 2021), which is complemented with federal policies to achieve comprehensive development of the CE (Li et al. 2021).

China is the second-largest productive economy globally, with high diversification in its national production, boosted mainly in the manufacturing and agricultural sectors, in which its economic development is highly related to the expansion of the manufacturing sector (World Bank 2020). However, the externalities of the economic boom have been reflected in the degradation of the environment (Zhang et al. 2020) due to the consumption of fossil energy, manufacturing and transportation (Liu et al. 2021). As a result, Chinese companies are under constant pressure to adopt clean production processes and mitigate environmental degradation. Therefore, CE and I4.0 applications are enterprise implementations (Wu et al. 2014) to drive a sustainable Chinese supply chain (Dong et al. 2021). Furthermore, CE and I4.0 have contributed to reverse the effect of COVID-19 (Su and Urban 2021).

In China, the adoption of I4.0 has been boosted and makes essential progress in improving supply chain performance, which has made the country considered one of the world leaders in the implementation of I4.0 (Li 2018). The technologies implemented in the Chinese supply chain are Cyberphysical systems, IoT, big data and analytics, cloud computing, artificial intelligence, blockchain, among others (Wang et al. 2020a; Xie et al. 2021; Yu et al. 2021). Similarly, China is expected to achieve carbon neutrality by 2060 by implementing sustainable production processes in the industry (Liu et al. 2021). This fact can be achieved by implementing CE practices, which it has been doing in recent years (Tang et al. 2020). The CE practices implemented in China are recycling and reuse, waste treatment, waste recovery, use of renewable energy, sharing maintenance services, control of resource performance, ecological design, among others (Zhu et al. 2010; Fan and Fang 2020; Wang et al. 2020b).

For this reason, this research aims to examine the relationship between CE and I4.0, COVID-19, considering some factors such as financing, environmental awareness, and Government environmental regulation, which are essential elements to consider in the transition to a CE. Thus, the research uses the Delphi approach to extract the opinion of several 54 experts in CE, with which relevant information can be obtained to understand the process of adoption of CE

in the country and its implication in the supply chain of the sector. Based on the call of the special number, we consider a qualitative approach that allows us to capture up-close information on a set of CE experts. This study constitutes unpublished material, based on the demanding review of the literature; a study of this nature has not been developed in the country, much less compiling the opinion of experts in the sector. Therefore, the contribution of the document can be evidenced in several directions: i) the study uses a qualitative Delphi approach, which compiles detailed information from experts in the sector; ii) the study provides information on the determinants of the CE; iii) the study provides a series of theoretical, practical and political implications; iv) a series of qualitative elements is used to answer the research question (RQ):

RQ: How do I4.0 and COVID-19 lead to CE adoption in firms in the sector in China?

Following the introduction, the remainder of the document is organized as follows: Sect. 2 contains the literature review and projections. Section 3 describes the qualitative methodology used. Section 4 contains the research findings. Finally, Sect. 5 contains the conclusions, policy implications and extensions of the work.

2 Literature review

2.1 Circular economy and COVID-19

COVID-19 brought several measures to counteract its spread; consequently, this action impacted several economic activities worldwide, causing problems in the functioning of the global supply chain (Nandi et al. 2021). Containment is one of the measures that caused a malfunction in the recycling supply chain in the maritime sector of Asian countries, given that this activity requires high participation of the workforce, this led to millionaire losses for the sector due to dependence on recycled materials (Rahman et al. 2021). Similarly, the use of disposable personal care products increased notably, under the determination that these supplies are infected and that they could hardly be reused, which reduces the adoption of sustainable practices, generating significant waste due to their indiscriminate use, typical of a biosafety procedure (Carenbauer 2021). However, this situation worsens much more, since added to the great demand for personal care products, the scarce recycling or waste recovery practices are added to mitigate more infections (Parashar and Hait 2021). Additionally, the increased demand for home delivery of food products requires large quantities of disposable packaging, generating more contamination (Vanapalli et al. 2021).

However, not everything is discouraging since the appearance of COVID-19 has accelerated the transition from a linear to a CE, thought about the reuse of resources, ecological design, among others (Wuyts et al. 2020). Likewise, the shortage of productive inputs due to the malfunction of the entire product supply chain has prompted firms to modify their production process to optimize resource use (Neumeyer et al. 2020). Similarly, due to the decrease in world production, energy-saving practices have increased, especially the use of renewable energy has been promoted, which contributes to a cleaner production process (Wicker et al. 2021; Wuyts et al. 2020; Ponce et al. 2021).

- P.1: COVID-19 has improved the eco-design of products.
- P.2: COVID-19 has improved efficiency and decreased resource waste in the production process.

2.2 Circular economy and Industry 4.0

One essential element for applying the CE is technological innovation because it provides multiple economic and environmental benefits and productive efficiency (Bag et al. 2021). Given the multiple barriers that arise in adopting the CE, I4.0 are presented as enablers of CE practices since their modern procedures facilitate the reuse of waste or waste purification (Jabbour et al. 2020a). Generally, I4.0 is used by intelligent component systems, integration of physical and digital systems, green product design, and all of these to improve the performance of inputs or the use of waste (Abdul-Hamid et al. 2020). The added value generated by I4.0 in the efficiency of resources, and therefore, in the establishment of the CE, is the reduction of processing times, integration in the supply chain, the flexibility of production processes, reduction of waste, among others (Bag et al. 2021).

Consequently, several types of I4.0 are instruments to accentuate CE processes (Khan et al. 2021b). For example, blockchain technology contributes to supply chain management, reducing costs, improve shipping times, reducing waste, improve communication between supply chain operators, among others (Upadhyay et al. 2021). Other technologies, such as the IoT, contribute to improved collection, transport and processing of commercial waste, consequently saving costs and reducing time in recycling processes (Arifatul et al. 2020). In the same sense, the design of products for reuse and recycling, the reduction in the costs of solid waste management and wastewater treatment have been feasible thanks to the adoption of cloud computing, IoT, intelligent objects, GPS, among others, becoming an enabler for CE practices (Bag et al. 2020).

- P.3: The implementation of I4.0 technology improves CE practices.
- P.4: The digital skills of workers enhance the role of I4.0 in CE practices.

2.3 Circular economy and financial resources

In Africa, concerns about caring for the environment do not seem to go unnoticed. Mutezo and Mulopo (2021) mention that the transition from polluting energies to fossils can be developed under the CE principles; hence the support of financial institutions is essential. Millette et al. (2020) indicate that the implementation of CE practices is viable through the hiring of firms that are in charge of managing waste and financing would be needed at the beginning of the implementation of the process, later the firm principal will assume the financing as risk capital.

In Scotland, there is continued support for a transition from a linear to a CE following the European Union's "Circular Economy Action Plan", considering consideration for the environment and environmental education of the United Kingdom in terms of financial support is weak, which puts the materialization of CE practices at risk (Whicher et al. 2018). In another country in the same region, Finland, Vanhamäki et al. (2020) mention that sustainable development strategies through a CE are possible in biogas production. On the contrary, this goal faces several financial challenges for implementing technologies that help in the process.

Several firms are oriented toward energy transformation under energy waste supply chain technologies within the United Nations framework. In contrast, obtaining financial resources to invest in technology and circular production processes counteract a clean production system (Ali et al. 2020). In the same sense, the conversion towards cleaner production can be achieved by managing a CE and adopting technology that facilitates these processes. Nevertheless, several barriers have been presented to implement sustainable production; the most important are economical and financial (Bhandari et al. 2019; Mignacca et al. 2020).

- P.5: The availability of financing from the firm itself allows the firm to adopt CE processes.
- P.6: The financing facilities constitute one of the main strengths for the adoption of CE practices.

2.4 Circular economy and environmental awareness

Concern for the environment is one of the main drivers for implementing the CE; however, it is a factor that has not been addressed in depth by academics (Liu and Bai 2014). Thus, for example, in the construction, engineering and architecture sector in the US, Guerra and Leite (2021b) mention that the transition towards a renewable economy is viable, despite the initial costs, the lack of regulations and the lack of environmental concern are some of the most significant barriers. Likewise, the implementation of the CE in construction in developed countries is unsatisfactory. An example of this situation is that energy transformation is the most developed, while waste management is the worst, under an environment where there is a lack of environmental concern on society and a lack of institutional regulations (Bilal et al. 2020). In the leather industry of emerging economies, Karuppiah et al. (2021) find several obstacles in implementing the CE; among the main ones are the uncertainty of consumer demand and the lack of social conscience in the environment. Therefore, Government entities must promote environmental awareness (Gunarathne et al. 2021).

On the contrary, in Poland, Smol et al. (2018) mention that concern for the environment is latent due to the tremendous economic boom and environmental degradation. Therefore, the CE is at the centre of attention to mitigate environmental degradation, with the environmental concern of the younger population being the main driver of the CE. Kinnunen and Kaksonen (2019) examine the drivers, barriers, and business opportunities in implementing the CE in the mining sector. Their findings show that environmental and technological awareness is one of the main drivers of the CE in the sector.

- P.7: Environmental awareness about environmental degradation encourages firms to implement CE practices.
- P8: Consumer demand leans for products whose firms apply CE practices.

2.5 Circular economy and government environmental policies

Government regulatory measures play a preponderant role in adopting CE practices (Schulz et al. 2019). For example, the remanufacturing industry in China has developed notably in recent decades due to institutional environmental reforms aimed at obtaining clean production processes under a CE approach (Yuan et al. 2020). Similarly, Närvänen et al. (2020) find in their study that CE practices are not born by the firm's initiative due to its environmental awareness but by laws and Government regulations that direct them to implement CE processes. In the same trend, Alonso-Almeida et al. (2021) mention an "institutional entrepreneur", governed by the regulations of each country from the European Union to implement CE practices.

In contrast, Fitch-Roy et al. (2021) indicate that the Government's role in implementing the CE in firms is present; however, the policies do not have the expected effectiveness. Besides, in developing countries, Hull et al. (2021) and Rweyendela and Kombe (2021) affirm these assertions, adding that entrepreneurs do not trust institutional environmental regulation and, on the contrary, many Government rulings worsen the implementation of the CE. Likewise, Jabbour et al. (2020b) establish that the Government role is incipient in adopting a CE process. Furthermore, Grafström

and Aasma (2021) define Government intervention as a barrier to implementing the CE since, in developed economies, the institutional infrastructure favours the linear economy.

- P.9: Government environmental policies oblige firms to apply cleaner production processes.
- P.10: Efficient Government environmental policies improve the adoption of CE practices.

3 Data and methodology

3.1 Delphi methodology

The Delphi method has many advantages within the experimental field; one is exchanging opinions between experts systematically and systematically among a group of experts. Furthermore, it is an approach that allows future projections on a specific topic (Van der Heijden 2011). This approach is developed through rounds, which allow for the fluid exchange of ideas among experts, the review of projections, and frequent feedback on responses (Wright and Giovinazzo 2000). The Delphi approach constitutes an adequate methodology to analyze the implementation of the CE due to the following aspects: i) the Delphi method provides a baseline to examine scenarios of high variability and constant modifications (Konu 2015). The COVID-19 outbreak shows several shortcomings in the production processes in the economy (Nandi et al. 2021). Therefore, academics foresee that I4.0 should become one of the main enablers to opt at once to transform the linear economy into a circular one (Jabbour et al. 2020a). However, despite the evidence of the benefits of I4.0 on CE implementation, these benefits during the pandemic are uncertain due to the rigidity that firms have in production (Sha et al. 2020).

Therefore, the Delphi approach is a methodological guarantee for analyzing the role of technology in volatile scenarios (Ivanov and Dolgui 2020). Additionally, the approach is suitable for understanding future situations such as I4.0. It will become an enabler of CE practices in firms. ii) due to COVID-19, the availability of reliable information is not readily available, which causes a restriction in applying research methodologies. Thus, the Delphi approach is the one that best fits in scenarios with little empirical information, and the criteria of experts on the subject offer an alternative for obtaining reliable information (Loo 2002). iii) the Delphi method uses the information collected from experts; for this reason, it becomes a source for obtaining information due to its greater precision than individual or group evaluations, through individual interviews or focus groups, respectively (von der Gracht 2008). In addition, it provides collaborative interaction between participants and, due to the

anonymity of the approach, allows to cope with any negative group eventuality that may arise (Linstone and Turoff 1975).

All these aspects mentioned above make the Delphi approach efficient and primary information can be handled first-hand during the COVID-19 pandemic with which a prospective study is generated in the CE through the application of I4.0, information that is currently limited in the literature, especially in developed economies (Ibn-Mohammed 2020). Consequently, the present study uses the Delphi approach to employ a comprehensive projection development process and develop a two-round web. The Delphi methodology follows the four steps shown in Fig. 1, described in the following sub-sections of this section.

3.2 Step 1: Projection development

As a requirement of the correct application of the approach, all the participants' orientations were directed to the future since the structured development of the projections is crucial for the value, validity and reliability of the Delphi study (Van der Heijden 2011). A workshop was developed with the research team and four practitioners with experience in CE processes from various industries as a starting point. All professionals agreed that the economic crisis caused by COVID-19 represented a reevaluation of the role of I4.0 in CE practices in firms. They were also considering the effect of COVID-19, environmental awareness and financing barriers. Likewise, the participants agreed that the current theory and pragmatism of I4.0 on CE in the industry should be updated, for which a comprehensive prospective study on CE is of great help in a scenario of uncertainty, such as it is that of a pandemic.

Second, the critical determinants of the role of I4.0 in enabling CE practices were identified to define a baseline on which the study projections are defined. Several sources were applied to apply the Delphi methodology correctly and comply with the rigour of the approach to obtain efficient and forceful results: i) a thorough review of the academic and professional literature; ii) workshop with four researchers; iii) 5 semi-structured interviews with firm executives that CE applies.

Third, for the definition of the projections, the guidelines of the approach for the formulation were followed, as well as the word count to guarantee validity and reliability (Salancik et al. 1975), that is, they were written, revised and I contrast them concerning their theoretical components. Ten projections were defined as recommended by Mitchel (1996), which allows to increase the response rate and reduce the incomplete filling of the information. The projections were formulated with a time horizon of 10 years until 203, considering previous CE studies with the Delphi method (Padilla-Rivera et al. 2020).
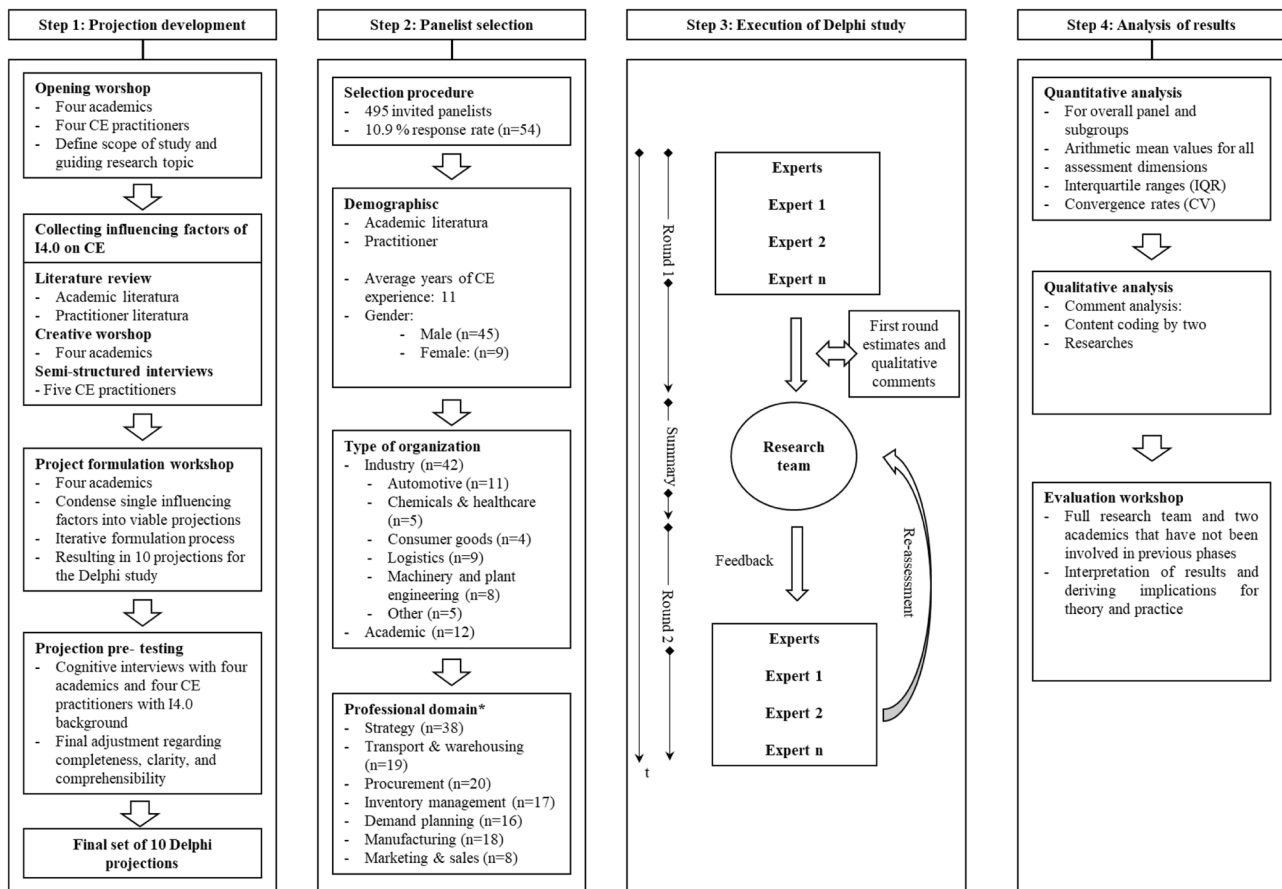
Fig. 1 Structure of Delphi research

Finally, four academics and four managers with considerable expertise in CE application processes were in charge of validating and providing feedback on the projections made, which was done through cognitive interviews. This procedure was performed to guarantee the study's robustness and validity through cross-validation and integrity tests (Sevillano et al. 2019).

3.3 Step 2: Panelist selection

The Delphi approach is based entirely on expert judgment; for this reason, the selection of panellists is rigorous and highly dependent on the quality of the research (Salancik et al. 1975). Thus, one of the main characteristics that experts must meet is a profound experience and various nuances to achieve quality results (Rowe and Wright 1999). To ensure selection bias, we followed the study by Spickermann et al. (2014) and the selection criteria are defined, considering the type of firm, current job position, academic training, and level of experience in CE and I4.0 processes. Based on exploratory analysis, 495 experts were identified and invited to participate in the study, including experts from academia

and industry representatives with CE responsibilities. From the experts identified, 54 experts from the country participated in the two rounds, representing a response rate of 10.9%; it is adequate given the experts' long experience and extensive processing period. The experts come from industry (42 / 77.8%) and academia (12 / 22.2%), with various professional domains.

3.4 Step 3: Execution of the Delphi study

The Delphi study is conducted in two rounds. In the first round, the panellists evaluate each of the ten projections. The evaluation dimensions of the projections are defined based on Delphi studies (Schmalz et al. 2020; Tunn et al. 2019) as follows:

- EP: the probability of occurrence of an event in a range from 0 to 100%
- I: Impact on the implementation of CE practices in the case of occurrence, taking as a reference a five-point Likert scale (very low = 1; low = 2; medium = 3; high = 4; and very high = 5).

- D: Expected occurrence scenario, based on the Likert scale of five response options.

Then, the panellists are asked to add any other information on the answer sheets in the quantitative evaluations for each dimension to capture qualitative criteria that have not been addressed in the quantitative collection through the Likert scale (Tapio et al. 2011). After the first round, descriptive statistics were generated based on the information collected from all the projections; likewise, the qualitative contributions were summarized. The results obtained were provided to the specialists to define the second round to reconsider their appraisals. Then, they were again asked to include qualitative contributions on the projections.

Subsequently, the non-response bias among the panellists should be verified. For this reason, a comparison is made between two groups of panellists who participated in the first and second rounds. The first ten and last ten are selected to answer in both rounds. Then, the application of the Shapiro–Wilk test on normality is carried out, which reveals a non-normal distribution of the selected sample (p-value < 0.05). Likewise, the Wilcoxon-Mann–Whitney test is applied; the results verify no significant differences between the two groups surveyed. These tests provide sufficient evidence to rule out the presence of non-response bias.

3.5 Step 4: Analysis of results

After performing the second round, the average values of EP, I and D of each proposed projection were calculated (Keller and von der Gracht 2014). In addition, the indicators of convergence rate (CV) and interquartile range (IQR) were calculated. The CV provides information on the evaluation changes globally; specifically, it examines the difference in the standard deviation for the EP between the two rounds of the Delphi approach. A negative CV explains that the panellists changed their statements and accepted that group after reviewing their colleagues' quantitative and qualitative arguments (Rowe and Wright 1999). In other words, the purpose of the consensual construction of group definitions had the expected result.

On the other hand, the IQR allows to know if the set of responses is dispersed or grouped according to each range; in addition, it allows examining the consensus of the Delphi study (Culley 2011; Lee 2014). Considering previous studies on CE with the Delphi method (Sevillano et al. 2019; Prieto-Sandoval et al. 2018), the IQR threshold < 25 is established as a parameter to affirm a consensus of the answers. In a range of 25% on a scale (0%—100%) of PE, at least 50% of the statements are there (Rowe and Wright 1999).

Subsequently, the information coding procedure proposed by Corbin and Strauss (2015) was applied to systematize the qualitative comments of the experts on each projection examined. Four categories were defined according to their projection inclination: positive, negative, neutral and not applicable. Positive ones represent arguments in favour of a high rating. Negatives mean arguments in favour of a low rating. Neutrals do not present an inclination but a general judgment—furthermore, those are not applicable when the statement is unclear. Two researchers specializing in information coding classified the comments individually. In addition, the consensus was reached on that information that showed divergence, thus achieving greater robustness of the information provided by the evaluators.

Finally, to conclude the Delphi analysis, the work team and two researchers from outside the Delphi study held a one-day workshop to socialize the results of the Delphi study and discuss them.

4 Results and discussion

4.1 Quantitative results

Table 1 represents the results of the CE experts' statements regarding each projection. The results are divided into two sections; the left part contains the projections, ER, IQR, CV, I and D. On the other hand, the right part contains the qualitative results coded using the procedure of Corbin and Strauss (2015). The EP ranges are widely defined, taking 35% for P.1 (ecological product design) to 88% for P.3 (4.0 technology). The impact registered high values ($I \geq 3.5$) in seven of the ten projections, considering P.5 (own financing), P.3 (Technology I4.0) and P.4 (digital skills) as the highest projections ($I \geq 4$). Likewise, the impact of P.1 was rated as the lowest ($I = 2.8$). On the other hand, the experts rated six projections as highly desirable ($D \geq 3.5$). No projection registered any value below three, which confirms the absence of possible threats. All CV values are negative, which shows the evidence favouring convergence in all the projections between both rounds; that is, the Delphi method was appropriately applied and worked adequately (Mitchel 1996). Likewise, the standard deviation decreased by 12.6% between both rounds; in addition, it decreased between 8 and 19% in all projections, which allows arguing a high convergence obtained in group consensus (Culley 2011). Consequently, the consensus was reached for four projections (P.3, P.4, P.5 and P.10) since their IQR values are lower than the defined threshold ($IQR \leq 25$).

Regarding the qualitative obtaining of the study, 714 written statements were obtained, approximately 13 qualitative comments for each participant. A high degree of interaction is evidenced since 80% of the participants made at least one comment. In addition, it was classified into two subgroups of industry (42) and academia (12). Additionally, a non-normal distribution was evidenced for each of the three dimensions (EP, I and D) in the two rounds (p-value < 0.05).

Table 1 Quantitative and qualitative results of the experts by projection

Quantitative results							Qualitative comments' trend				
No	Projection	EP [0–100%]	IQR [0–100]	CV [-100%-100%]	I [1–5]	D [1–5]	Supportive	Negative	Balanced/ neutral	n/a	Sum
P.1	Eco product design	35%	30.8	-22%	2.8	3.1	35	13	18	1	**67**
P.2	Resource efficiency	44%	34.3	-18%	3.4	3.4	25	13	17	-	**55**
P.3	Technology 4.0	88%	*18.5*	-15%	4.2	4.4	51	9	21	2	**83**
P.4	Digital skills	85%	*20.2*	-25%	4.1	4.2	58	12	37	3	**110**
P.5	Own financing	77%	*22*	-19%	4.1	4	37	17	19	1	**74**
P.6	External financing	60%	34	-11%	3.8	3.9	32	12	18	-	**62**
P.7	Environmental awareness	62%	38	-21%	3.6	3.6	40	13	20	-	**73**
P.8	Consumer demand	42%	35	-10%	3.3	3.2	24	11	17	1	**53**
P.9	Government policies	55%	38	-8%	3.7	3.2	28	16	21	-	**65**
P.10	The efficiency of Government policies	75%	*19.3*	-18%	3.9	4.3	40	13	18	1	**72**
Sum							**370**	**129**	**206**	**9**	**714**

IQR ≤ 25: panel consensus in italics

EP Expected probability, *D* Desirability, *IQR* Interquartile range, *I* Impact, *CV* Convergence (i.e., decreased standard deviation

Complementarily, the Wilcoxon-Mann–Whitney test was applied to evaluate possible differences between the responses of the projections in the two subgroups. The results showed that the tests of the evaluations of EP and D of P.1 (design of ecological products) differed significantly ($p < 0.05$). There are no more deviations in the evaluations between subgroups; in other words, the results of the Delphi study have great credibility and validity, which strengthens that the experts raised comparable projections without autocorrelation (Prieto-Sandoval et al. 2018).

4.2 Discussion of projections

First, we have the P.3, P.4, P.5 and P10 projections with high ratings across the dimensions (EP > 70%, I > 3.5, D > 3.5). These projections show negative convergence rates (between -25% and -15%) and an IQR ≤ 25, revealing that the experts are sure of their prognosis and have reached a consensus on the matter.

This finding is the projection with the highest probability of occurrence, impact and desirability of all the study projections, which indicates a significant influence on the future of the CE. (P.3) I4.0 technology: Panel experts predict that I4.0 is one of the main enablers for applying CE in firms. They foresee that the I4.0 is decisive to accelerate converting a linear economy to a CE one by 2030. In addition, they mention that state-of-the-art technological procedures must strengthen the processes (reduce, reuse, recycle) of the CE for inputs since this will allow them to implement the process efficiently and does not delay conventional production processes. Several experts affirm that the reuse of products

or inputs requires a transformation process to be used again as raw material, so I4.0 makes the process more efficient and with excellent results.

Besides, other experts mention that blockchain technologies, IoT, sensors, artificial intelligence, among others, provide adequate information for successful decision-making and efficient use of resources. Some others stated that robotization is a highly used tool due to its high efficiency and low waste of resources, which underpins the CE optimization processes. These statements complement the findings of Arifatul et al. (2020), who demonstrated that the I4.0 help the adoption of the CE due to the improvement in the waste collection processes or the recycling activities.

Digital skills (P.4): Experts consider workers' digital skills to be crucial for implementing the CE in 2030. The impact and desirability of this projection are high, which reveals the importance of skills workers to implement clean production processes in the industry. Workers' digital skills provide them with better training and more capacity to manage I4.0; it generates a more efficient process because it allows them to analyze the data better and, consequently, make the right decisions. Likewise, experts affirm that workers' digital skills in the industry are relatively low in the country's industry. Therefore, firms should be concerned with investing in I4.0 without neglecting the digital specialization of workers to operate I4.0 successfully.

In addition, several panellists affirm that the role of I4.0 is crucial and vital in the transformation towards an economy; however, I4.0 would not have the expected effect if there were digital deficiencies of the workers. These results are consistent with Bag et al. (2021), who indicate that workers'

skills improve the analysis of big data or artificial intelligence, which improves CE adoption. Therefore, digital skills and I4.0 complement each other to achieve a successful effect on CE adoption.

Own financing (P.5): The panellists consider that the availability of resources is crucial to financing the implementation of the CE by 2030. The CE production processes assume a different design compared to the linear economy. Therefore, monetary resources are needed to leverage these actions, so financing is one of the main barriers to adopting the CE. The panellists affirm that two factors condition the financing of the resources. One, the availability of monetary factors makes it easy for the firm to invest in a cleaner production process. Second, there is uncertainty about the future benefits obtained by producing under a circular scenario despite having the financing.

These statements are consistent with what was expressed by Lekha et al. (2021), who affirm that COVID-19 has seriously affected firms, which require financial aid to stay in the market and cover their financial obligations. Financing has become a crucial factor today, given that COVID-19 has disrupted firms' operations, resulting in fewer resources to invest in a productive transformation. Thus, many firms have problems cancelling their credit obligations acquired before COVID-19; therefore, trying to cover new obligations aimed at a productive transformation becomes a scenario with very remote probabilities.

Policy Efficiency (P.10): Consensual expert evaluations predict that the Government's regulatory role is crucial for a sustainable economy by 2030. The definition of Government policies to mitigate environmental degradation is a sample of an express concern to recover the environment. However, the panellists suggest that, in addition to legal and Governmental regulatory standards, these must be of quality and promote convergence towards a CE; that is, the policies must be effective. Panellists consider this screening to have a considerable impact and be highly desirable. Some of the qualitative opinions expressed by the panellists agree that the Government (in addition to defining policies for circular adoption) should play a more active and participatory role in the implementation from a more technical perspective, guiding and training firms in the CE adoption.

Equally important, they consider that the Government should incentivize firms that promote CE implementation in their production. The quality of Government policy is crucial; this is why Rweyendela and Kombe (2021) affirm that the efficiency of Government policies should be efficient; otherwise, Government policies become an obstacle to adopting a CE without effectiveness.

In this sense, experts agree that the manufacturing industry should focus on I4.0 in workers' digital skills, financing the firm itself, and environmental quality regulation as the most probable and high impact factors for adopting the CE in 2030.

Next, we have the projections with PE between 55 and 62%. These projections have been rated and discussed with controversy, given that its IQR is above 30. These findings find evidence in favour of slightly positive trends concerning its achievement of the CE until 2030. The impact and desirability values are between 3 and 4 points, respectively.

Environmental awareness (P.7): The panellists highlighted that environmental concern is essential in adopting the CE by 2030. This concern is associated with the depletion of natural resources and a linear production model based on obtaining, using, and throwing out. The panellists then assume that this rampant and increasingly growing demand can be mitigated through a more sustainable production process that relies on the reuse of discarded factors, either through recycling or obsolete products.

Several panellists explain that environmental awareness is a crucial factor in adopting CE; however, it must support Government entities to have more impact on its tasks. Likewise, some of the experts' annotations affirm that COVID-19 has increased the concern of the environment and has set off the alarms to change towards a productive process with less dependence on new natural resources. In the study by Liu and Bai (2014), he agrees with these findings, who affirm that environmental awareness is essential, but it has gone unnoticed since it has not been given the necessary importance. The panellists showed moderate confidence about the applicability of the projection for the year 2030.

External financing (P.6): When firms have monetary resources, financing for CE implementation is more viable. On the contrary, when the firm does not have this financing facility, the situation is more complex, and the firm managers must look for other alternatives, which are not always very encouraging. In general, the participants agreed in affirming that external financing can eliminate the barrier of lack of resources to invest in I4.0 to obtain efficient CE processes, statements that are in the sense of recent empirical research (Bhandari et al. 2019; Vanhamäki et al. 2020).

These findings are related to the dimensions of EP of 60% and an IQR = 34. However, financing is not always easy to achieve since the participants affirm that there is not a high supply of financing defined explicitly for adopting technologies aimed at sustainable production changes. So the panellists were very undecided about whether external funding will be widely developed to be considered one of the drivers for achieving the CE in 2030. Some of the experts' qualitative statements mention that external financing for the implementation of the CE must come as a law by the Government, in which banks are pressured to offer this type of financial product.

Government policies (P.9): Government regulation policies are a preponderant factor in achieving the CE's implementation in the industry. Its appearance denotes a negative externality in the environment, a production model that

degrades the environment. Therefore, its design forces firms to adapt to new production processes that guarantee economic and social sustainability. However, the value of the dimensions is not very encouraging, which indicates that there is no clear definition that establishes that the policies give the impetus in favour of the adoption of the CE.

Fitch-Roy et al. (2021) find results that are in line with the findings of this projection; they indicate that policies by themselves fail to promote the CE, policies must be directed in such a way that actions help firms they have not become an obstacle. When policies are incipient, the Government's role becomes inefficient in reaching the CE (Jabbour et al. 2020b). This situation creates uncertainty about the role of policies to achieve circular production in the industry in 2030.

Consequently, the findings of the projections result from P.6, P.7, and P.9 do not have a clear position to reach the CE in 2030; on the contrary, they generate uncertainty and proof of this are their probabilities of occurrence.

Resource Efficiency (P.2) and Green Product Design (P.1): COVID-19 significantly affected economic operations globally. This situation evidenced the significant problem of keeping the economy linearly in which dependence on new resources and materials is highly risky. Thus, several approaches arose to have a circular production model in which resources are used by recycling or reusing decomposed products. The experts revealed that firms tend to improve resource use in a scenario of uncertainty and risk. However, behind the efficiency of resources and the design of ecological products, there are other determining factors to improve productive factors. First of all, there must be a level of technology that allows it to adapt to this circumstance and to be able to adapt its process. Moreover, decisions to switch to a CE during a pandemic are less viable due to this decision's significant investment.

In this context, P.2 and P.1 have a low expected probably due to the evaluators' criteria divergence. Experts consider that COVID-19 is not considered a determining factor in modifying the production process to a cleaner one. On the contrary, it has accentuated the problem of lack of monetary resources to finance this situation.

Consumer demand (P.8): Consumers choose products from firms that apply production processes with low environmental impact. Experts mention that this approach is associated with the new generations with greater attachment and concern for environmental issues (Karuppiah et al. 2021). In the same way, they mention that the growing demand for green products generates more incentives for firms to adopt CE production processes and capture new market niches. However, although there are valid reasons, experts warn that this projection is very unlikely to occur from the demand for organic products. This is because there is no defined formal position, nor does it support the entities

in charge of the Government to give greater prominence to this position. In addition, the experts affirm that the quantity of demanders of these types of products does not represent the necessary demand to influence the firm's decisions. Experts doubt consumer positioning will become a driver to improve CE adoption in the industry through 2030.

In this context, according to experts' opinions, the effect of COVID-19 generated imbalances in the Chinese supply chain management due to policies to mitigate the spread of the virus. However, the implementation of CE practices allowed the improvement of the functioning of the supply chain. Similarly, the paralysis of economic activities due to COVID-19 has been an opportunity to project scenarios in which CE practices are implemented. This scenario considers a clean energy transition, which reduces carbon emissions by 40% (Su and Urban 2021). This fact constitutes an improvement in the company's environmental performance and consequently contributes to a green supply chain (Dong et al. 2021). On the other hand, the reestablishment of the firms' operations led to the advancement of the supply chain. This fact occurs due to the adoption of I4.0, such as blockchain, which allows improving the firm's management in the distribution of products and enhances the exchange of information and logistics between the supply chain operators (Umar et al. 2021). Likewise, the implementation of business data analytics made it possible to improve the delivery times of products to end consumers, with which the supply chain was re-established. Consequently, the implementation of CE practices improves firm performance, which translates into an improvement in the supply chain functioning that was severely affected by COVID-19.

Finally, the analysis of the last three projections reveals an unlikely scenario for COVID-19 and consumer demand to become determinants for adopting the CE by 2030. Experts reveal several doubts regarding compliance with these three projections.

5 Conclusions

The recession due to COVID-19 has affected global economic activities and has also impacted the environmental sustainability of the economy. Based on a thorough review of the CE literature, some determining factors are identified, such as I4.0, COVID-19, financing, environmental awareness, and Government environmental policies. I4.0 is identified as one of the main determinants to drive the application towards a more sustainable production through an economy that reuses, reduces and recycles resources. Consequently, ten projections are made on how these variables will affect the CE by 2030. The study is carried out through a Delphi approach, considering 54 CE experts, 42 CE experts in the industry and 12 academics. These specialists were in charge

of evaluating the ten projections through three dimensions: the probability of occurrence, impact, and desirability of occurrence. Additionally, the approach allows the inclusion of qualitative contributions from the experts, coded using the Corbin and Strauss (2015) procedure and considered for the analysis.

From the results obtained, the panellists' contributions are highlighted, who are experts in the sector and provide first-hand information to know the context and projections of the CE, considering the effects of COVID-19 on the economy. The projections with the highest values are P.3, P.4, P.5 and P.10; these contribute to the CE's implementation. The results obtained reveal important implications for theory, practice, and policy formulation that strengthen the CE in the long term.

5.1 Implications for theory

The theoretical contributions of the present investigation can be defined in several ways. In the first place, it is one of the primary studies in integrating and combining the role of I4.0, accompanied by COVID-19, financing, environmental awareness and Government policies, in future research related to the CE. Following the special issue of the journal, this study provides quantitative and qualitative contributions from CE experts, which covers the wide gap in the literature on the availability of this type of study. Furthermore, the Delphi approach of the present study generates qualitative input from CE experts, which is generally not captured in empirical studies. Second, the results obtained from the study raise several questions about the implementation of CE and its implementation is expected to increase in the future. Likewise, the development of digital capacities is crucial with the role of I4.0 in adopting the CE since they are complementary factors that stimulate the achievement of sustainable production of firms. Like the own financing, which firms require to start the productive transformation of the firm, the same one that takes on greater importance in the face of the COVID-19 crisis. Additionally, with a view to 2030, the Government's environmental policies are expected to change from a linear economy to a circular one since experts believe it is one of the fundamental pillars of achieving a CE. Third, although I4.0 development will increase in 2030, the study reveals that some of the I4.0 will be implemented at different times. However, it is expected that the Government's support, effective policies, and due financing will strengthen the CE's implementation. In contrast, the projections with a lower PE show some factors that were not determining when drawing up a roadmap to lead to a CE. Finally, an empirical perspective of the post-COVID-19 path is proposed in the CE context, providing critical information to the academic community on how to conceptualize the adoption of the CE after COVID-19.

5.2 Implications for practice

At the managerial level, significant practical and strategic contributions are seen for the adoption of the CE. First, the findings confirm the benefits of I4.0 in CE without neglecting the digital capabilities of workers to drive CE, so managers must follow a holistic perspective to integrate I4.0 into the firms. Second, the importance of financial autonomy is identified since it becomes one of the main barriers to adopting the CE. Therefore, managers must see how they allocate a significant part of their budget in investing in the productive transformation of the firm since it requires a significant investment. Third, it is identified that the Government's role is crucial in implementing the CE, as long as the policies are efficient and managed technically and operationally to coordinate this implementation with the firm. Therefore, managers should consider forming a specialized team in the CE field to obtain all the Government guidelines to interpret the CE implementation process correctly. Finally, managers must consider that the productive transformation towards the digitization of production processes can also be started by developing by implementing digital skills of the firm, which will mean the first steps towards a technological production oriented to the adoption of CE.

5.3 Implications for policy

The research makes a significant contribution on the role of I4.0 on CE, as well as the role of financing, and the efficiency of Government environmental policies, which should be considered of interest to policymakers because they will help them define best measured under scenarios of uncertainty such as the current pandemic that we are going through. Thus, several policy implications can be drawn from the findings reached. First, it is demonstrated that I4.0 facilitates the adoption of the CE. In the context of China, policy implications should consider that the adoption of I4.0 shows significant advances; however, I4.0's implementation should be promoted to increase CE practices in firms. In China, some advances need to be strengthened in CE to achieve the objectives set out in the "Made in China 2025" Project. Therefore, policymakers should encourage firms or even comply with a technological transformation that guarantees cleaner production. Complementarily, workers' digital skills should be improved to increase the efficiency of I4.0 over CE. This state guideline must be accompanied by a system of economic incentives which rewards firms that adopt sustainable practices in production. Likewise, firms can be incentivized by reducing the tax burden, subsidies, or promoting the products of said firms in local and international markets to encourage their commercialization.

Second, the study shows strong evidence on self-financing as a determinant of CE adoption. In this sense, the Government

should force firms to invest part of their economic benefit in technological improvements or CE implementation. Complementarily, the participants, indicate that external financing is weak, for which the Government should demand that the public and private banks define more facilities for the issuance of credits aimed at investing in I4.0 and CE, respectively. Likewise, provide preferential interest rates to provide payment facilities to firms that will invest in this type of activity. Similarly, the Government should require financial institutions to form specialized teams on I4.0 and CE to provide better advice on implementing I4.0 and CE. Considering the situation in China, credit products should be established that are aimed at financing activities related to I4.0 and the CE. This fact will allow firms to have more excellent support and imposed to implement clean production processes based on I4.0 processes.

Finally, the experts mention that Government policies must be adequate; otherwise, they would not generate the expected effect in adopting the CE and become obstacles. China must propose its economic growth objectives based on the Sustainable Development Objectives. To achieve these goals, the institutional framework and specialization of the technical teams involved in production with CE through I4.0 must be strengthened. Governments must be prepared with technical and trained personnel who provide quality advice and support in firms. Governments should consider forming a specialized technical group and training it to implement CE adoption policies in the industry, considering experiences from countries in the region or countries with high technological development on CE.

5.4 Limitations and future research

The study contributes significantly to the current state of the literature on CE; however, it contains certain limitations that can be used for future research, including the following. First, the study refers to the fact that I4.0 offers several benefits in CE's adoption. However, it does not refer precisely to which types of technology, nor does it indicate which technology is better than another, nor does it indicate the effectiveness they have in the adoption of the CE Second, the study qualitatively identifies the barriers to the implementation of the CE; despite the interrelationships, levels of influence or strategies to overcome them are not studied. Third, the study design used individual evaluations in the achievement of the CE in manufacturing firms. Nevertheless, a greater understanding of their interrelationships is needed, which would increase the CE implementation. Finally, the number of projections was limited to ensure the completion of the survey; given that the study phenomenon is extensive, there are other issues to be investigated.

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