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A comprehensive minimum cost consensus model for large scale group decision making for circular economy measurement

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ABSTRACT

Since the first report on the Circular Economy (CE) appeared in 2013, there has been an explosion of interest in the subject by society and the business world. Thus, a base of academic literature has been developed, seeking the establishment of principles that serve as a theoretical foundation for the concept of CE. Governments demand to know how organizations are evolving in the transition towards the new production model. However, despite the efforts of researchers and companies to develop effective measurement systems, it is not easy to decide which aspects to measure, nor to determine the degree of intensity in which an organization implements the CE model. The measurement proposals combine different methodologies that are costly and time consuming procedures. We propose a comprehensive minimum cost consensus model for large scale group decision making, in which the initial experts' preferences are automatically adjusted to obtain the measurement and cost of indicators, so that they might agree on the measurements implemented. The main aim of this research is not only to provide a quick, useful and correct method for measuring the CE, but also to show its correctness, advantages and usefulness by comparing its performance with a real case.

1. Introduction

The Circular Economy (CE) consists of the simultaneous consideration of environmental and economic aspects with the aim of maintaining the value of products, materials and resources in the economy as long as possible, and minimizing waste generation (Górecki et al., 2019; Lewandowski, 2016; Molina-Moreno et al., 2017; Witjes and Lozano, 2016). Its objective is to move away from the traditional linear approach to the economy (extraction, manufacturing, use and disposal) to a new circular one, which modifies the traditional life cycle of products, paying attention to the use of materials and resources (water and energy, among others), introducing a closed cycle for economic purposes (Nasir et al., 2017). This increases efficiency in the use of resources, especially in industrial and urban areas, achieving a better balance and harmony between the economy, the environment and society. The main causes of the impact industry has on the environment are based on the use of non-renewable resources and the generation of polluting residues, which are increasing at an accelerated rate (Esa et al., 2017; Rivero et al., 2016). The effect is the significant destruction of the natural capital stock (Presti, 2013) as a result of entropic degradation, an issue that is particularly tangible when we observe its most visible or known effects, such as the loss of native forest, the depletion of fossil, fuels, the reduction of water reserves and pollution of the atmosphere through the emission of greenhouse gases, acid rain and the destruction of the ozone layer (Wadel et al., 2010). Thus, the CE is a bid to reduce the negative impact of organizations on their surrounding environment. The CE is a model that pursues the long-term sustainability of companies, and its implementation will determine a new production model, guaranteeing the survival of organizations, such as Cradle to Cradle, which will have to progressively adopt its principles eventually (Braungart et al., 2007; Mulhall et al., 2013). More initiatives are also needed for sustainable production and the use of sustainable sources, as they will minimize the waste generated and reduce the amount of and care required for the materials used during the manufacturing, production and maintenance phases (Nasir et al., 2017).

On the other hand, while we can find abundant literature on the

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implementation of the CE, the issue of measuring it remains unexplored and more efforts are neeeded on the behalf of researchers (Elia et al., 2017; Frank, 2015; Moraga et al., 2019). The generation of CE efficient measurement scales will allow two things to happen: firstly, organizations will be able to identify whether they are applying a CE or not, and how strongly they are progressing towards this new model (Elia et al., 2017; Sassanelli et al., 2019; Scarpellini et al., 2019). Secondly, stakeholders will be able to find out the company's position on this issue. Once the need of generating measurement scales of CE implementation has been highlighted, the next step would be to determine which are the most efficient methods that can be used to generate such scales. As observed in the literature review performed, the transition process appears to be complex (Guzzo et al., 2021) as there are a series of obstacles that make measuring the CE a difficult task. Firstly, there are no previous scales that can be used as a basis from which to start, and secondly, we do not know which variables to use for measurement.

The problem arises when there is a scarce and limited number of indicators for measurement (Veleva et al., 2017). In fact, there is no generally accepted monitoring framework for CE measurement (Parchomenko et al., 2019). For this reason, having to decide what types of indicators to use and, what levels and topics to analyze has become a major obstacle in the measurement process (Moraga et al., 2019). Among the CE evaluation methods that are currently being developed, we can find the following: Data envelopment analysis life (Expósito and Velasco, 2018), Cycle Analysis (Angelis-Dimakis et al., 2016), Multiple-criteria decision analysis fuzzy methods (Iakovou et al., 2009) or Monte Carlo simulations (Górecki et al., 2019; Núñez-Cacho et al., 2020b).

Thus, due to the still incipient state of CE research and the complexity of measuring it, authors have frequently had to resort to groups of experts. They provide useful information for the design of the measurement instruments, determine which are the dimensions that make up the measurement scales, and which will be the variables to be analyzed. For instance, Alaerts et al. (2019) propose meetings with experts in workshops involving stakeholders from the public administration, the society and other companies as being a possible source of indicators. Following the proposal of the indicators, the experts provided their feedback and a database was modeled. Another method for generating indicators to apply the CE is the one developed by Núñez-Cacho et al. (2018a). The authors propose a mixed process that incorporates indicators grouped around the following main topics: energy, resources, water, negative externalities, and CE principles. To do so, they created a database with 208 indicators from two sources: (i) a review of the literature and (ii) an analysis of the sustainability reports of large companies in the construction sector. Subsequently, after organizing the database, refining the indicators and generating a questionnaire, it was then submitted to a Delphi method process via online survey. A measurement scale for CE was then generated for companies in the construction sector using the results obtained.

However, although these methods generate reliable indicators, they are time-consuming to implement and, in most cases, involve a very high cost and do not always reach a successful solution, as the experts involved often leave the process before it finished. Thus, a specific conceptual theoretical framework for the CE has been developed that has established the characteristics and principles of the new CE model. So, different public administrations, and society in general, want to know how the production system mechanisms are progressing in more sustainable production models from an economic, social and environmentally sustainable point of view, demanding that the public and private entities start implementing strategies for the transition to a CE (Alaerts et al., 2019; Núñez-Cacho et al., 2020b). For this reason, measurement systems, such as the creation of indicators that help decision-makers understand and determine the degree of intensity of the transition of a company and organization when implementing the CE model in its production and service delivery system, are in high demand.

According to these arguments, the purpose of this paper is to establish a consensual, reliable, feasible, low-cost, quick and efficient methodology to select indicators applicable to the measurement of the CE. Therefore, we aim at studying the application of a methodology based on a Comprehensive Minimum Cost Consensus model (CMCC) (Labella et al., 2020) in which experts provide their initial indicators preferences and the CMCC model looks for a consensus on the measurements in an quick and automatic way, providing the cost required to achieve such consensus in order to inform the stakeholders about the convenience of attaining consensus on some indicators. This model can easily obtain the agreed measurements, the cost for achieving such an agreement and useful indicators in just seconds instead of having to spend months asking experts to change their preferences in different rounds. Our proposal is based on large scale group decision making (LSGDM), meaning that it can with large number of experts. In the literature something is considered to be a LSGDM when there are at least 20 experts involved (Chen and Liu, 2006), but in general there are a lot more. It may be also adapted in cases with less experts if necessary, but the idea for CE measurement in real world problems aims at dealing with large group of experts (Modgil et al., 2021). In addition to the main aim of this research, which is to provide the previous methodology to measure the implementation of the CE, we intend, at the same time, to show its validity and verify its effectiveness, therefore we will replicate the real case of the study carried out by Núñez-Cacho et al. (2018a), which will allow us to draw conclusions about the effectiveness of the CMCC model dealing with larger scales in the CE environment and point out future research on this topic.

The research questions that stem from our objective are:

- RQ_1 : Which method allows us to efficiently select the indicators that measure the implementation of the CE in an organization?
- RQ_2 : In what ways is this method more efficient than others that have been developed to date?

To sum up and clarify our research, the main novelties of this contribution are the following:

- To provide a novel and efficient method to measure the degree of implementation of the CE in organizations by using a CMCC model for large groups.
- To minimize the time taken to achieve consensus on the measurements.
- To contrast the application of the proposed method by replicating a study on the same subject as that of (Núñez-Cacho et al., 2018a) based on a different methodology.
- To obtain effective measurement instruments to boost the applicability of the CE and cover the gaps identified to date in terms of measurement.

The remainder of this paper is structured as follows: Section 2 makes a revision of the concept of the CE and its framework and reviews the CRP for LSGDM. Section 3 introduces some concepts about CRP dealing with LSGDM and the concept of MCC. Section 4 explains the large scale CMCC model which is used to select the indicators. Section 5 shows the advantages of the proposed model by means of a performance study comparison and an analysis of the results is introduced in Section 6. Finally, Section 7 points out some conclusions and future work.

2. Literature review

In this section a deep revision is made about the concept of the CE and its framework. Moreover, a review of CRP dealing with LSGDM has been included.

2.1. Concept of circular economy

The concept of CE has deep-rooted origins and cannot be traced to a single date or author. However, its practical applications to modern economic systems and industrial processes have gained momentum since the late 1970s, led by a series of theoretical contributions that form the basis of the CE. These schools of thought that underly the CE are essentially as follows: In the first place, the Performance Economy (Stahel and Reday-Mulvey, 1976). These authors stated that more manpower and fewer resources were needed to renovate existing buildings instead of erecting new ones. They included the vision of an economy in cycles or loops (or circular economy) that, in addition to having a positive impact on job creation and economic competitiveness, meant saving resources and reducing waste generation. Later, the idea of regenerative design arises, developed from the principles of agriculture and initially applied to architecture. This idea of regeneration is one of the foundations of the CE framework. As early as 1980, the term “circular economy” was used (Pearce and Turner, 1990) to describe a system of interactions between the economy and the environment. The Cradle-to-Cradle (C2C) philosophy is also considered to be one of the origins of the CE. The products are designed and manufactured in such a way that to avoids contaminating the environment, not only during the manufacturing processe, but also throughout their useful life. C2C-based production involves a circular industrial system where all materials are used indefinitely. Materials, at the end of their useful life, can become a primary resource, theoretically without loss of quality, and are then used to manufacture the same product again or a different one. This general process can be considered an “ascending cycle” (Contreras-Lisperguer et al., 2017).

One of the most influential schools of thought on which the CE is based is the Theory of Industrial Ecology. This theory presents the industry as an ecosystem (Hook and Paolucci, 1970) and applies the principles of the Theory of Human Ecology to the study of the interaction and interdependence of industries and the environment, forming a basic ecological framework for decision-making (Paolucci, 1977). The theory of Industrial Ecology presents a synthesis of assumptions, concepts and propositions of various disciplines of ecology and of the general theory of systems, as it is useful to describe and explain not only the interactions that occur within industries, but also those that occur within the environment. This is a science-based perspective, but it also applies principles, methods and results to daily activities (Bubolz and Sontag, 1993). This theory refers to the “creation, use and management of resources for adaptation, human development and the sustainability of environments”, focusing on the interactions between industry and the environment.

The well-being of the industry cannot be separated from the well-being of the entire ecosystem (Brown et al., 1989). In this way, we must find a balance between the demands of the ecosystem and those of individuals as a whole. The core values of the theory are the survival of businesses, the sustainability of the environment, and the pursuit of the “improvement” of the situation. Another key concept included in the CE is biomimicry. Benyus (Benyus, 2003) uses this concept to explain how scientific innovations are inspired by the way nature behaves. The author defines her approach as a new discipline that studies the best ideas of nature and then imitates these designs and processes to solve human problems. She thinks biomimicry is a nature-inspired innovation. Biomimicry is an approach taken by nature to face the challenges of sustainable development (social, environmental and economic). Biomimetics describes the interdisciplinary cooperation of biology and technology or other fields of innovation, with the aim of solving practical problems through the analysis of the functions of biological systems, their abstraction into models and the transfer and application of these models to the solution (Hayes et al., 2020).

Nature can be thought of as a type of capital (natural capital) that provides essential contributions to human health, prosperity, and well-being. However, economic activity that leads to climate change, loss of biodiversity, and other causes of ecosystem degradation has resulted in a risky and costly loss of natural capital. Economics has a central role to play in analyzing the value of natural capital and in designing incentives to conserve and restore it (Polasky and Daily, 2021). Finally, the Blue Economy, which insists that solutions are determined by their local environment and their physical / ecological characteristics suggest that gravity is a primary source of energy.

Based on these approaches, the CE has set itself the primary objective of reducing negative externalities by recycling and reusing existing resources. It is currently defined as being a restorative and regenerative industrial economic model thanks to its intention and design (Ghisellini et al., 2016; Lieder and Rashid, 2016). So, the production system regenerates the inputs used, uses renewable energies and diminishes waste generation via careful design. The CE seeks to minimize the negative externalities generated. Krugman (2010) highlighted the link between market exchanges and negative externalities (costs incurred by third parties, when the first two; buyers and sellers, carry out economic transactions). Negative externalities can manifest as costs related to economic, environmental and / or social sustainability for third parties and society in general (Laczniak, 2017). In this way, we establish that the consumption of resources, waste generation and emissions are the main negative externalities generated by organizations, and so, are the indicators to measure and minimize.

The CE can be considered to be a response made by organizations to environmental requirements in order to guarantee the survival, maintenance and sustainability of the environment. Several key dimensions support the concept of the CE, such as the idea of a product as a service (Witjes and Lozano, 2016), Cradle to Cradle principles, ecoefficiency, technological nutrients and the minimization of the negative externalities generated (Blériot, 2013; Núñez-Cacho et al., 2020a).

The CE considers a product to be a service, which means that the use of products can be sold, but not the material. The customer simply uses the product and the supplier is responsible for introducing it into the reproduction process. During the design phase, concepts such as modularity, versatility and adaptability are managed, which are the most important properties in a changing world (Tukker, 2015). Besides, the CE considers that the production and consumption of the goods should follow the principles of the 3 Rs (reduce, reuse, recycle), which contribute to reducing the pressure on the global resources stock (Reh, 2013), respecting the environment and guaranteeing the sustainability. Similarly, the C2C concept (McDonough and Braungart, 2002) proposes attacking the root of the problem. Thus, rather than reducing energy consumption, we must focus on the concept of any product, strategy or policy itself, taking into account all the phases of the products involved (extraction, processing, use, reuse, recycling). CE is also supported by biomimetics that aims to apply the principles of biological cycles to the life cycle of technological elements (Lieder and Rashid, 2016). We must imitate the biological recycling process of nature by applying it to industrial materials (Blériot, 2013). The CE is also based on the concept of ecoefficiency, which can be defined as the simultaneous ability of an organization to achieve its economic objectives by degrading the environment to the least extent possible (Stępień et al., 2021). This implies that any material, whether waste or not, can be reused in any production chain. In addition, it is necessary to minimize the energy absorbed by the material and, if possible, ensure that this energy comes from a renewable source (Bonciu, 2014). Industrial processes must include interactions with the natural systems that surround them. Finally, products or services that are not consumed, but that provide a specific service to the user, must remain in closed technical cycles so that they are safe and can be reused (Shao et al., 2019).

The CE model provides solutions to the environmental costs generated as a result of production and consumption processes. This implies that any production system must manage its inefficiencies to prevent or reduce environmental damage. All these environmental damages are referred to as negative externalities, and they originate in consumption decisions, production, exchange of inputs / productive factors and investment (Núñez-Cacho et al., 2020a).

2.2. Circular economy framework

Since the CE is at an early stage of development, one of the main problems it faces is the degree to which a company implementing CE is measured (Mayer et al., 2019). The proposal introduced by Geng et al. (2012) highlights the lack of indicators on sustainability in the industry, which is a challenge for both researchers and companies. Both the dimensions to be measured and the indicators to be used are topics that researchers are currently striving to obtain approval for. The problem that arises in these new disciplines is that there are no scales available that have been previously validated by the literature, so construction and validation processes must be undertaken using one method or another. The Delphi technique is flexible and very suitable when there is incomplete knowledge about the phenomena; especially when the objective is to improve the understanding of problems, opportunities or solutions, or to develop forecasts (Skulmoski et al., 2007).

In an effort to provide measurement tools to companies, Núñez-Cacho et al. (2018a) developed a measurement scale based on an initial set of 234 indicators, obtained from the literature review and analysis of company reports. The rules of the Delphi method were established to analyze the qualifications of the experts and decide if an indicator was to be accepted, refused or if it needed to be revised. Table 1 shows the rules that (Núñez-Cacho et al., 2018a) used in their work for the development of the e-Delphi method. These criteria are established to accept or reject an indicator depending on the descriptive statistics of the sample, such as arithmetic mean and standard deviation, in accordance with the generalized Delphy methodology standards.

where i refers to an indicator, $\overline{X}_i$ is the average of the expert evaluation, 1 being very important and 5 of very little importance, $\overline{x}^*_L$ and $\overline{x}^*_U$ represent the interval values related to the acceptability of the indicator regarding its average, δ_i represents the standard deviation of the valuation made and δ^*_1, δ^*_2 the acceptance threshold regarding the standard deviation.

It should be highlighted that the Delphi method (see Remark 1) has its limitations (Fink-Hafner et al., 2019). For example, the characteristics (multiple dimensions and indicators) in this process require a long time horizon in order for the method to be completed successfully. In addition, it is time consuming for both researchers and participants. There are several work rounds, with their corresponding time intervals and also several processes required to present the results, which explains why Delphi is vulnerable to attrition. Participants may also drop out due to prolonged engagement, distraction between rounds, or disillusionment with the process (Donohoe and Needham, 2009). The financial cost of carrying out the different rounds should also be highlighted, especially when consensus is not reached and several interventions are required, in addition, the synthesis and presentation techniques of the coordinating group's responses are frequently deficient, which can lead to the abandonment of experts between rounds.

Table 1
Initial Delphi method rules (Núñez-Cacho et al., 2018a).

N°	RULE	Action
1	$\overline{X}_i > \overline{x}^*_U$ and $\delta_i > \delta^*_1$	Reject
2	$\overline{X}_i > \overline{x}^*_U$ and $\delta_i < \delta^*_1$	New round
3	$\overline{x}^*_L < \overline{X}_i \leq \overline{x}^*_U$ and $\delta_i > \delta^*_2$	New round
4	$\overline{x}^*_L < \overline{X}_i \leq \overline{x}^*_U$ and $\delta_i < \delta^*_2$	Accept
5	$\overline{X}_i \leq \overline{x}^*_L$	Accept
6	Few or no changes in the response panel occur in round	End of review

2.3. Revision of consensus models for large scale group decision making

LSGDM has attracted the attention of many scholars who have proposed different consensus models that deal with LSGDM to cope with some challenges, such as: opinion polarization, scalability, non-cooperative behaviors, supervision, the uncertainty of information and support systems to deal with large numbers of experts. Here we revise the most recent ones.

Song and Li (2019) presented a consensus model for LSGDM that represents a sub-group's preferences by means of multi-granular probabilistic fuzzy linguistic preference relations and obtains the weights for the alternatives using a programming model based on consistency. Several proposals have studied the use of heterogeneous information to model experts' preferences and have defined different consensus models (Tang et al., 2019; Zhang et al., 2018b). Li et al. (2019) and Xiao et al. (2020) point out that it is important to keep in mind that "words mean different things for different people" and this is something that is usually ignored in the current models. As such, they have developed CRP-LSGDM by using the personalized individual semantics model that considers specific semantics for each expert. Zha et al. (2019) defined a CRP-LSGDM model with a bounded confidence-based optimization approach that includes a feedback mechanism that is able to produce more acceptable advice to try and reach a greater level of consensus. The management of non-cooperative behaviors has been also studied by means of punishing experts' preferences or punishing their weights (Du et al., 2020; Li et al., 2021; Xu et al., 2019). Rodríguez et al. (2018) introduced a new approach to keep as much information as possible during the CRP by using the concept of hesitant fuzzy sets and to compute the relevance of experts' sub-groups by taking into account not only their size, but also their cohesion. Wang et al. (2019) developed another consensus model for LSGDM that obtains the sub-groups' weights by considering their size and the importance of the experts within the sub-group. Some approaches have used hesitant fuzzy linguistic term sets (HFLTS) to represent experts' preferences and have defined new consensus models for LSGDM. For instance, Ren et al. (2020) present a social network analysis-based clustering method to group experts and define an approach for managing minority opinions. Rodríguez et al. (2021b) introduce a cohesion measure for HFLTS based on restrictive equivalence functions to obtain the subgroups' weights and define an adaptive feedback process that provides recommendations to experts or a sub-group of experts according to the consensus level achieved in order to reduce the time cost. Gao et al. (2020) propose a clustering-based consensus model for LSGDM that introduces a k-core decomposition method to recognize leaders' opinions in the social networks built according to a new similarity measure. Trust relationships have commonly been studied to compute experts' weights and to provide experts with suggestions for modifying their preferences, however Du et al. (2021) highlight that they can also be used to manage non-cooperative behavior. Therefore, they define a consensus model to reduce experts' preferences and deal with non cooperative behavior by means of a trust-similarity measure that takes internal and external features of the clusters into account. Another consensus model for LSGDM introduces an estimating method based on the collaborative filtering algorithm and the concept of opinion leaders to obtain the missing preferences of opinion leaders (Li and Wei, 2020). It also develops a new feedback process to help the sub-groups of experts to modify their preferences. A novel consensus model based on minimum cost when dealing with LSGDM that studies preference has recently been proposed in (Rodríguez et al., 2021a) and Lu et al. (2021) have introduced a minimum cost consensus model based on robust optimization. The main idea of minimum cost is to reach consensus with the least possible changes in experts' preferences, which is very important in problems dealing with hundreds or thousands of experts.

All these models attempt to address the different challenges presented by real-world LSGDM problems.

3. Research method

This section introduces Consensus Reaching Processes for Large Scale Group Decision Making and explains the meaning of Minimum Cost Consensus to make the proposal easier to understand.

3.1. Consensus reaching process for large scale group decision making

Due to society's demands in decision making (Eklund et al., 2007; 2008) and technological development, the number of experts involved in Group Decision Making (GDM) problems has increased in current real world group decision problems (Xiao et al., 2020). These kinds of problems are called LSGDM problems and consist of:

- A set of alternatives $X = \{x_1, \ldots, x_n\}$, $(n \geq 2)$, which can be selected as a possible solution for the problem.
- A set of experts $E = \{e_1, \ldots, e_m\}$, $(m >> n)$, who express their assessments on the set of alternatives X.

The solving scheme of an LSGDM problem is similar to a GDM problem that consists of two phases (Roubens, 1997) (i) aggregation, in which the experts' preferences are fused to obtain a collective opinion and (ii) exploitation, in which a ranking is obtained to select the best alternative(s). However, several tasks should be considered in LSGDM in order to deal with specific challenges (Labella et al., 2018; Rodríguez et al., 2018).

The above-mentioned two-step solving process does not guarantee an agreement among all experts involved in the decision making problem, and some conflicts might arise as some of the experts might think that their opinions were not taken into account and therefore might not agree with the solution. In order to overcome this drawback, a CRP has been included in the solving scheme before obtaining the solution (Butler and Rothstein, 2006).

A CRP is a dynamic and iterative process in which experts that taking part in the problem modify their preferences. This aims at obtaining a more acceptable solution for all experts by trying to diminish the differences between them in order to reach a collective opinion (Parreiras et al., 2010). A general CRP scheme is sketched in Fig. 1 and described below.

- *Framework configuration*: in this phase the set of alternatives, the set of experts and the consensus threshold to be reached are defined.
- *Gathering preferences*: the preferences provided by experts are collected.
- *Computing consensus degree*: the level of agreement in the group of experts, noted as μ in this contribution, is computed.
- *Consensus control*: the level of agreement obtained in the previous phase is compared with a consensus threshold fixed a priori. If the consensus threshold is achieved, a selection process starts to select the best alternative, otherwise another discussion round is necessary.
- *Feedback process*: the experts' preferences that provoke disagreement are identified and some recommendations are generated to help experts modify their preferences and bridge their differences in order to increase the level of agreement in the next round.

It is harder to achieve agreement in LSGEM problems because the opinions of a large number of experts tend to more conflictive and polarized (Dong et al., 2019), thus, a CRP is required before selecting the best solution for the LSGDM problem. A taxonomy that classifies the consensus models into four different types according to their performance was introduced in (Palomares et al., 2014) (see Fig. 2).

The consensus models belonging to Q1 and Q2 use a feedback mechanism to help experts bringe their differences. Nevertheless, this feedback process might imply an excessive change in the original experts' preferences and, thus, also imply a high cost consumption and a very time-consuming process. Therefore, the cost of modifying the experts' opinions is key in CRP and this becomes more important when a number of experts are involved in the problem. For this reason, this proposal uses an automatic CRP without a feedback process that is based on the minimum cost concept, which minimizes the cost to achieve the desired level of consensus.

Remark 1. Delphi is a common feedback based method that has commonly been used in many real-world group decision making problems. Delphi is a process to achieve consensus in which experts express their opinions by using questionnaires, which are aggregated and shared with the group after each round. Experts can modify their opinions based on how they interpret the group opinion in order to increase the

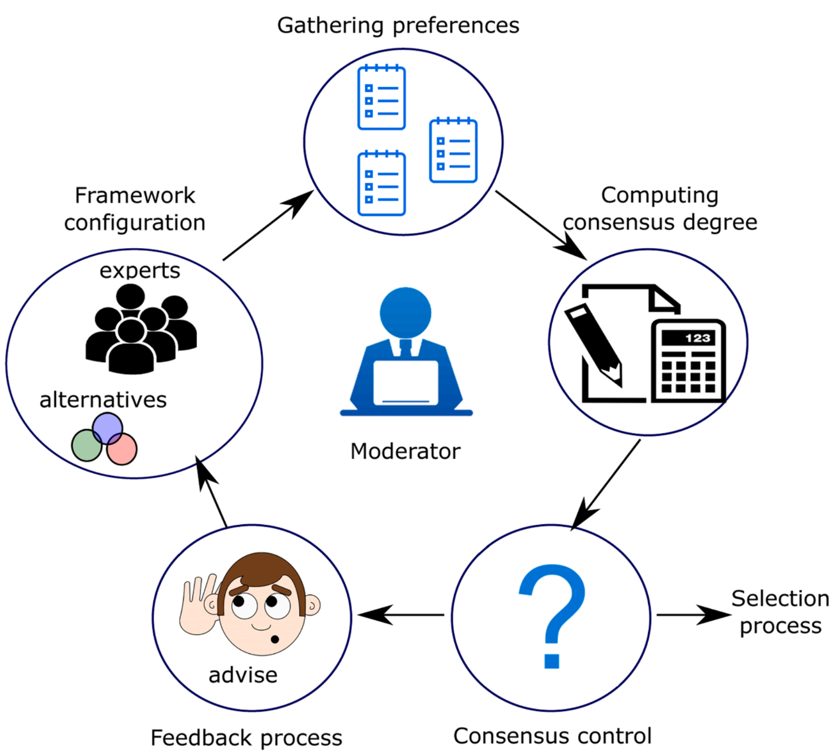

Fig. 1. General scheme of a CRP.

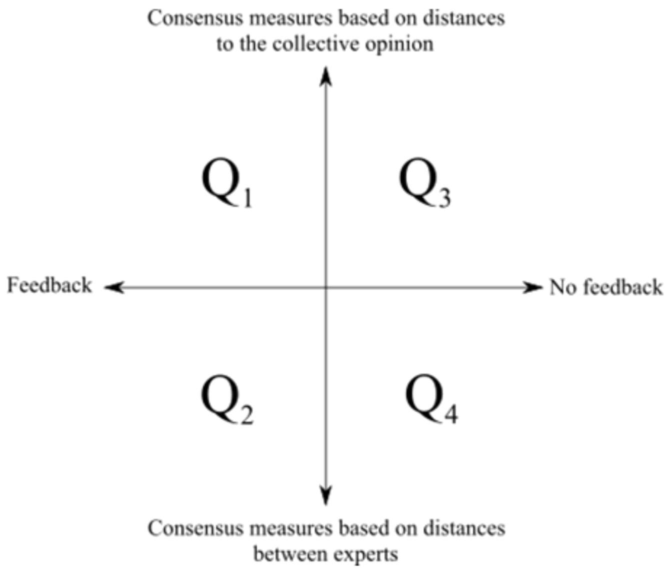

Fig. 2. Taxonomy of consensus models.

consensus level in the next round (Skulmoski et al., 2007).

3.2. Minimum cost consensus

The concept of MCC was defined by Ben-Arieh and Easton (2007) as *"consensus is achieved when the distance between experts and the collective opinion is minimum"*. By using this concept, Zhang et al. (2011) introduced the following MCC model to minimize the cost of modifying experts' preferences:

Definition 1. (Zhang et al., 2011) Let $(o_1, \ldots, o_m)$ be the assessments provided by a set of experts $E = \{e_1, \ldots, e_m\}$ over an alternative, and c_k be the cost of moving expert e_k's opinion 1 unit. The MCC model based on a linear cost function is given as follows:

$$(\mathbf{M-1})$$
$$\min \sum_{k=1}^{m} c_k |\overline{o}_k - o_k|$$
$$s.t.\ |\overline{o}_k - \overline{o}| \leq \varepsilon, k = \{1, \ldots, m\}$$

where $(\overline{o}_1, \ldots, \overline{o}_m)$ are the adjusted experts' opinions, $\overline{o}$ is the collective opinion, ε is the maximum acceptable distance of each expert to the collective opinion. Therefore, if the expert's opinion is in the interval $[\overline{o} - \varepsilon, \overline{o} + \varepsilon]$, it is not necessary to change it, otherwise the opinion should be changed until that expert's opinion is exactly ε away from $\overline{o}$.

Taking this model into account, Zhang et al. (2011) proposed another MCC model that studies how the aggregation operator used to aggregate the experts' opinions and obtain the collective opinion can affect how the consensus level is computed. It is defined as follows:

$$(\mathbf{M-2})$$
$$\min \quad \sum_{k=1}^{m} c_k |\overline{o}_k - o_k|$$
$$\text{s.t.} \quad \begin{cases} \overline{o} = F(\overline{o}_1, \overline{o}_2, \ldots, \overline{o}_m) \\ |\overline{o}_i - \overline{o}| \leq \varepsilon,\ k = \{1, \ldots, m\} \end{cases}$$

where $F : [0,1]^n \rightarrow [0,1]$ is an aggregation operator used to obtain the collective opinion

Over time, different MCC models have been introduced in the literature (Cheng et al., 2018; Gong et al., 2015; Labella et al., 2020; Li et al., 2017; Rodríguez et al., 2021a; Zhang et al., 2018a).

4. Proposed method: A large scale comprehensive minimum cost model in the circular economy

It has been pointed out that the evaluation of the degree of implementation of the CE in companies is not a simple task, since there is no predefined list of indicators that has been globally accepted by the community. For this reason, it is common to ask expert groups directly about their preferences by using methodologies such as the Delphi method (Núñez-Cacho et al., 2018a). However, these methodologies constantly require the participation of a large number of experts and it can take a long time to obtain results. For this reason, we propose a new methodology based on a large scale CMCC model in which experts just provide their preferences once, and review rounds are not strictly necessary. Additionally, such a method provides information about the cost required to reach mutually agreed upon solutions that can be used if considered either for justifying the need of a "new round" or for justifying the impossibility of accepting an indicator (see Fig. 3).

Remark 2. For the sake of simplicity, in this proposal we consider that the cost of changing an expert's opinion is 1 unit, but there are some models that compute this cost, for instance, Zhang et al. (2020) obtain the cost by means of an optimization model and fix its value within an interval whose upper and lower sides are predefined according to the problem.

4.1. CMCC model

The CMCC model selected for the new methodology was recently proposed by Labella et al. (2020), who pointed out that small distances between experts and the collective opinion did not always guarantee that a desired level of agreement would be reached, that we should also consider the consensus among experts in order to obtain a more acceptable solution for the group. In order to illustrate this, let us introduce an example:

Example 1. In a CE framework three experts provide their preferences for an indicator by using a scale from 0 to 1, so $o = \{0.99, 0.45, 0.12\}$. The aim is to reach a solution that all the experts agree on. We consider $\mu = 0.85$ to be a logical consensus threshold to try to achieve. However, by using the model (M-2), we can only set the minimal distance between the modified experts' preferences, $\overline{o}_k$ and the collective preference, $\overline{o}$, through ε. Table 2 shows the consensus achieved in the group with different values of ε. Note that with some of them, the desired level of consensus $\mu = 0.85$ is not reached. Therefore, setting a minimum distance between experts and the collective opinion does not always guarantee that an acceptable group solution will be reached.

For this reason, Labella et al. (2020) proposed a CMCC model that considers not only the distance between experts and the collective opinion, but also tries to achieve a minimum agreement in the group. This model is defined as follows:

$$(\mathbf{M-3})$$
$$\min \quad \sum_{k=1}^{m} c_i |\overline{o}_k - o_k|$$
$$\text{s.t.} \quad \begin{cases} \overline{o} = A(\overline{o}_1, \overline{o}_2, \ldots, \overline{o}_m) \\ |\overline{o}_k - \overline{o}| \leq \varepsilon,\ k \in \mathbb{I}_m \\ \mathbb{C}(\overline{o}_1, \overline{o}_2, \ldots, \overline{o}_m) \geq \mu \end{cases}$$

where the function $\mathbb{C} : [a,b]^n \rightarrow [0,1]$ measures the consensus level among experts and $\mu \in [0,1]$ is the consensus threshold.

Therefore, Labella et al. included an additional condition related to the computation of the experts' group consensus ($\mathbb{C}$). In this way, it is possible to set a desired level of consensus to be achieved within the group of experts and to guarantee a consensual solution in which most of

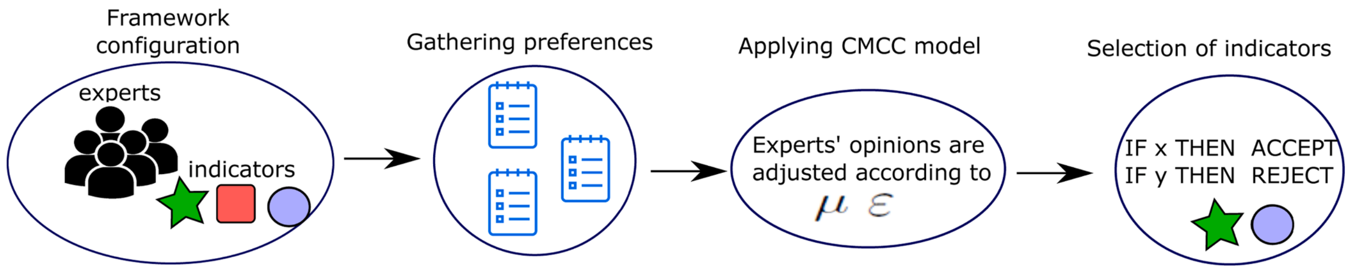

Fig. 3. Scheme of the proposed model.

Table 2
Consensus achieved by using (M-2).

ε	μ
0.5	0.58
0.15	0.83

them agree. If we refer back to Example 1, with model (M-3) we can always guarantee that the desired level of consensus, $\mu = 0.85$, is reached, regardless of the value of ε.

According to the taxonomy described in (Palomares et al., 2014) and shown in Fig. 2, there are two types of consensus measures used to compute the consensus level: (i) consensus measures based on the distance between experts' opinions and collective opinion and (ii) based on the distance between the experts' opinions. Labella et al. (2020) introduced CMCC models for each consensus measure, but in this contribution we have chosen the type of consensus measure explained in (i) for sake of simplicity (although both types may be used). This model is defined as follows:

$$(\mathbf{M-4})$$

$$\mathfrak{c} = \min \quad \sum_{k=1}^{m} c_k |\overline{o}_k - o_k|$$

$$\text{s.t.} \quad \begin{cases} \overline{o} = \sum_{k=1}^{m} w_k \overline{o}_k \\ |\overline{o}_k - \overline{o}| \leq \varepsilon, \ k = \{1, \dots, m\} \\ \sum_{k=1}^{m} w_k |\overline{o}_k - \overline{o}| \leq 1 - \mu \end{cases}$$

where $w = (w_1, w_2, ., w_m)$ are the experts' weights in the GDM problem.

Note that big differences in experts' opinions on an indicator would imply a low level of consensus and thus, the experts would need to change their initial preferences to achieve a consensual solution. This would, therefore, cause a high cost for the CMCC model (M-4). Fig. 4 shows an illustrative example of this, in which the experts' opinions are initially far apart from one another and consequently, the consensus degree is low $\mu = 0.6$. Therefore, it is necessary to change the experts' preferences in order for them to agree on a solution ($\mu = 0.85$). At the same time this implies a high resulting cost $\mathfrak{c} = 23.8$. Therefore, it seems logical to think that the cost of changing opinions may be a key aspect to take into account in the acceptance of the indicators.

4.2. *New rules for acceptance and rejection of indicators in the CMCC model*

The new methodology here introduced aims to select indicators that can be applied to measure the CE. Therefore, several rules must be defined that determine if an indicator is accepted or not based on experts' preferences. Furthermore, such rules have allowed fair comparisons to be made with other methodologies in order to evaluate the performance of our proposal in relation to others.

We propose general rules of acceptance and rejection of indicators based on the ones introduced in Section 2.2. These new rules also consider the average and standard deviation as measures that evaluate the acceptance of the indicators, but we also include an additional condition related to the *resulting cost* obtained from the CMCC model (M-4). In this way, those indicators that require a high cost to achieve the solution and thus, great changes to be made to experts' preferences, are candidates to be rejected (see Table 3).

where i refers to an indicator, $\overline{X}_i$ is the average of the modified ex-

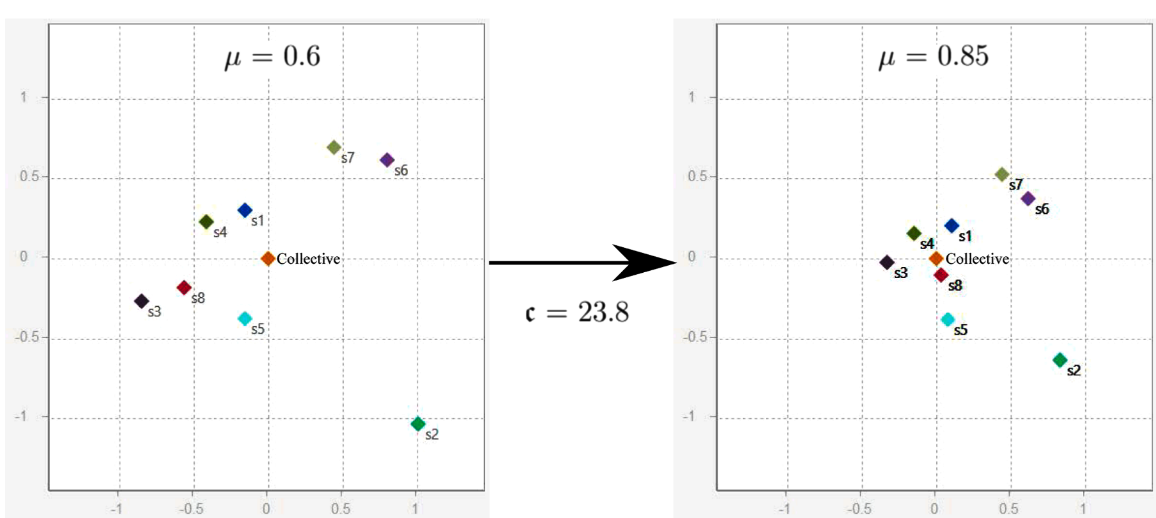

Fig. 4. Cost of reaching consensus with preferences far that are initially apart from one another.

Table 3
CMCC methodology rules.

N°	RULE	Action
1	$\overline{x}_L^* < \overline{X}_i < \overline{x}_U^*$ and $\delta_i < \delta^*$ and $\mathfrak{c}_i < \mathfrak{c}^*$	Accept
2	$\overline{X}_i \leq \overline{x}_L^*$ and $\mathfrak{c}_i < \mathfrak{c}^*$	Accept
3	otherwise	Reject

perts' preferences $\overline{o}_k$ obtained from the CMCC model, $\overline{x}_L^*$ and $\overline{x}_U^*$ represent the interval values related to the acceptability of the indicator regarding its average, δ_i represents the standard deviation of such modified preferences and δ^* the acceptance threshold regarding the standard deviation, $\mathfrak{c}$ the cost of changing experts' preferences obtained from the model (M-4) and $\mathfrak{c}^*$ the acceptance threshold regarding the cost.

Remark 3. Note that, the acceptance threshold values related to the average, standard deviation and cost used in the rules shown in Table 3 are not set with constant values. These values depend on the individual requirements of each indicator and also on the global characteristics of the decision problem analyzed.

5. Experimental framework and results

5.1. The case study of "what gets measured gets done: Development of a circular economy measurement scale for building Industry": LSGDM resolution, analysis and comparison

In order to show the performance and advantages of our proposal, we use the CE case study introduced in (Núñez-Cacho et al., 2018a) and carry out a performance study comparison between the methodology used in such contribution based on Delphi and our proposal based on a CMCC model for large scale GDM. Núñez-Cacho et al. (2018a) explain the reasons why the construction sector is one of the sectors that requires more attention due to its high negative externalities. It stresses that the application of the CE would improve its long-term sustainability. The problem that the authors intended to cover with this study is the measurement of the degree of implementation of the CE, due to the absence of psychometric measures. The work describes the generation of step by a step the measurement scale for the CE in the construction industry by applying the Delphi research technique.

The initial questionnaire was administered via a web application. Initially, a database made up of 81 experts who were invited to participate in the panel was built. The experts were selected from academics involved in civil engineering, sustainability and economics problems in different universities; from professionals involved in international think tanks that support sustainable production to scientists united in the international mail group "Co-operative Network for building researchers". An acceptance rate of 48% was achieved, with a total of 39 experts agreeing to join the panel.

The parameters related to the acceptance rules and the CMCC model are defined for the case study.

5.1.1. Rule parameters

First of all, the conditions of acceptance of the indicators must be defined. These conditions are determined by the rules shown in Table 3. Taking into account that experts express their opinions on the indicators by using a numerical scale in which 1 is very important and 5 is of very little importance, the values assigned to the parameters related to the rules are shown in Table 4.

Remark 4. The values of $\overline{x}_L^*$, $\overline{x}_U^*$ and δ^* have been assigned in order to carry out a proper comparison with the proposal introduced in (Núñez-Cacho et al., 2018a), since the authors use these values in the Delphi rules. The value of $\mathfrak{c}^*$ has been assigned taking into account that the experts provide their preferences by using a scale from 1 to 5 and

Table 4
Parameter values for rules.

Parameter	Value
$\overline{x}_L^*$	1.5
$\overline{x}_U^*$	1.9
δ^*	0.85
$\mathfrak{c}^*$	2.5

thus, the individual maximum resulting cost must be 4. With $\mathfrak{c}^* = 2.5$ we restrict the number of changes in the experts' opinions, since experts are not usually receptive to making either many or big changes to their initial opinions.

5.1.2. CMCC model parameters

The CMCC model (M-4), used to automatically modify the experts' preferences, introduces four parameters: (i) the cost of modifying the e_k expert's opinion (c_k), (ii) the e_k expert's weight (w_k), (iii) the minimum accepted distance between the modified experts' preferences and the collective opinion (ε) and (iv) the desired level of agreement to be reached in the group (μ). The values of these parameters, described in Table 5, have to be properly assigned so that a fair comparison can be made with the methodology introduced in Section 2.2:

The value of ε, it is determined by the rules defined in Table 6 such that:

- Rule 1 represents the case in which it is not necessary to change the initial experts' preferences. If the standard deviation of the experts' preferences for an indicator (δ_i) is equal or lower than the threshold value (δ^*), then the preferences are close enough to each other and it is not necessary to reach consensus. For this reason, with $\varepsilon = 5$, the initial experts' preferences would not be modified (the experts' evaluations range from 1 to 5) and consequently $\mathfrak{c}_i = 0$. The acceptance or rejection of the indicator will depend on the rules introduced in Table 3.
- If the condition in rule 1 is not satisfied, then the experts' preferences are automatically changed by the model (M-4). The value of ε depends on the experts' opinions on each indicator. The smaller the value, the greater the cost and the greater the probability of rejecting the indicator.

Remark 5. Note that, for this contribution, if $0.85 < \delta_i < 0.9$ then $\theta = 2.5$ otherwise $\theta = 1.5$.

5.2. Resolution

Table 7 shows the results regarding the acceptation and rejection of the indicators in both approaches. In the case of the Delphi approach, the results are divided into the two revision rounds that were necessary in (Núñez-Cacho et al., 2018a) to obtain the final selection of indicators.

5.3. Comparison

Analyzing Table 7 in further detail, we can appreciate that our proposal returns the same decision for the indicators accepted and rejected in the *first round* of Delphi, which validates our proposal. In addition,

Table 5
Parameter values for rules.

w_k	$w_k = 1/m,\ k \in \{1,\ldots,m\}$
c_k	$c_k = 1,\ k \in \{1,\ldots,m\}$
μ	0.85
ε	Determined by rules (Table 6)

Table 6
ε values .

N°	RULE	ε
1	$\delta_i \leq \delta^*$	5
2	otherwise	θ

although 38 indicators are accepted in the first round of Delphi, the CMCC proposal directly accepts 46 (see Table 8). The 8 additional accepted indicators will be also accepted in the second round of Delphi. Therefore, our proposal is not only in line with the experts' decisions about the accepted indicators in the first round, but also anticipates some of their future decisions in the second one.

However, our proposal does not provide exactly the same results obtained with the Delphi methodology (see Table 9). It is necessary to take into account that the CMCC model automatically modifies the experts' opinions by satisfying some restrictions defined in such a model to reach an agreement minimizing its cost, but in some situations the minimum cost required to reach consensus could be *high*. On the other hand, in Delphi methodology, the experts are asked to change their initial opinions again and, depending on their (un)cooperative behavior, may agree to change their initial opinions or not and, obviously, this is something that a non-linear programming model cannot manage. Although our proposal does not provide the same results, it obtains only false negatives (indicators accepted in Delphi methodology are rejected in our proposal), and no false positives (indicators rejected in Delphi methodology are accepted in out proposal), and there is more than 90% correspondence in the decisions about the indicators (see Table 9).

The false negatives are the result of an excessive cost in changing the experts' preferences. From our point of view, the cost of modifying experts' initial preferences in these 8 indicators is very high, which means that initially the experts' opinions are quite far apart from one another and that the indicators should be rejected. Table 10 shows that the total cost obtained for the 8 indicators is clearly higher than the acceptable cost threshold defined in the CMCC rules shown in Table 3 ($\mathfrak{c}_i < 2.5$).

The indicators i_8, i_{25}, i_{28} and i_{48} present the highest values of cost (12.85, 18.54, 25.57 and 11.27 respectively). This mean that the experts' opinions on these indicators are quite far from one another, and that trying to reach a consensual solution would require too many changes. Therefore, we consider that experts' opinions are so far apart that it would be difficult for experts to agree on the acceptance of the indicator. The rest of indicators rejected do not present such a high cost, but it is high enough to show that there are disagreements concerning the opinions made, and that making a decision, either to accept or reject, may not be fair for some experts.

Remark 6. Based on previous results, it seems suitable to point out that the adjustment of a suitable cost for each problem in order to accept or reject the indicators would be worthy of future research.

6. Discussion

The CE requires valid instruments to measure its degree of implementation in companies/organizations. The development of these measurement instruments is complex and costly for the organizations involved. In addition, each of the industrial sectors, with their specific characteristics, require their own indicators, which leads us to a scenario in which multiple measurement scales are required, with different multiple indicators. The challenge therefore consists in proposing a method for developing these efficient measurement scales.

The complexity and cost of effective CE measurement has been managed by group decision making schemes that involve many experts and stakeholders and in which the Delphi method has also played a key role in the resolution process. However, recent and novel LSGDM methods have been proposed to deal with such problems by reducing the time and cost incurred to achieve a collective and/or agreed upon

Table 7
Results.

Indicator	$\overline{X}$	δ	$\mathfrak{c}^*$	Delphi (round 1)	Delphi (round 2)	CMCC proposal
i_1	3.71	0.88	1.0	Reject	-	Reject
i_2	1.5	0.63	3.87	New round	Reject	Reject
i_3	1.42	0.83	0	New round	Accept	Accept
i_4	1.39	0.5	0	New round	Accept	Accept
i_5	1.39	0.56	0	New round	Accept	Accept
i_6	1.27	0.63	0	New round	Accept	Accept
i_7	1.39	0.75	0	New round	Accept	Accept
i_8	1.59	1.03	12.85	New round	**Accept**	**Reject**
i_9	1.64	0.78	0	Accept	-	Accept
i_{10}	1.39	0.61	0	Accept	-	Accept
i_{11}	1.64	0.78	0	Accept	-	Accept
i_{12}	1.55	0.56	0	Accept	-	Accept
i_{13}	1.88	0.7	0	Accept	-	Accept
i_{14}	1.5	0.76	19.56	New round	Reject	Reject
i_{15}	1.5	0.75	18.57	New round	Reject	Reject
i_{16}	1.48	0.76	0	Accept	-	Accept
i_{17}	1.52	0.76	0	Accept	-	Accept
i_{18}	1.52	0.71	0	Accept	-	Accept
i_{19}	1.52	0.8	0	Accept	-	Accept
i_{20}	1.42	0.79	0	Accept	-	Accept
i_{21}	1.73	0.72	0	Accept	-	Accept
i_{22}	1.61	0.83	0	Accept	-	Accept
i_{23}	1.89	0.66	0	Accept	-	Accept
i_{24}	1.83	0.69	0	Accept	-	Accept
i_{25}	1.5	0.77	18.54	New round	**Accept**	**Reject**
i_{26}	1.85	0.87	4.23	New round	Reject	Reject
i_{27}	1.69	0.79	0	Accept	-	Accept
i_{28}	1.5	0.75	25.57	New round	**Accept**	**Reject**
i_{29}	1.82	0.7	0	Accept	-	Accept
i_{30}	1.6	0.79	3.34	New round	Reject	Reject
i_{31}	1.76	0.83	0	Accept	-	Accept
i_{32}	1.66	0.82	0	Accept	-	Accept
i_{33}	1.94	0.86	10.12	New round	Reject	Reject
i_{34}	1.89	0.83	9.16	Reject	-	Reject
i_{35}	1.5	0.64	6.54	New round	Reject	Reject
i_{36}	1.87	0.83	3.33	Reject	-	Reject
i_{37}	1.87	0.83	2.33	Accept	-	Accept
i_{38}	1.5	0.58	32.62	Reject	-	Reject
i_{39}	1.27	0.52	0	Accept	-	Accept
i_{40}	1.42	0.66	0	Accept	-	Accept
i_{41}	1.89	0.82	1.79	New round	Accept	Accept
i_{42}	1.79	0.7	0	Accept	-	Accept
i_{43}	1.84	0.75	0	Accept	-	Accept
i_{44}	1.69	0.66	2.82	New round	Reject	Reject
i_{45}	1.64	0.84	0	New round	Accept	Accept
i_{46}	1.84	0.81	3.44	Reject	-	Reject
i_{47}	1.5	0.75	12.52	Reject	-	Reject
i_{48}	1.43	0.74	11.27	New round	**Accept**	**Reject**
i_{49}	1.33	0.71	4.44	Reject	-	Reject
i_{50}	1.42	0.79	0	Accept	-	Accept
i_{51}	1.5	0.72	10.53	Reject	-	Reject
i_{52}	1.21	0.6	0	Accept	-	Accept
i_{53}	1.7	0.88	9.74	New round	Reject	Reject
i_{54}	1.5	0.73	3.51	New round	**Accept**	**Reject**
i_{55}	1.42	0.61	0	Accept	-	Accept
i_{56}	1.48	0.83	0	Accept	-	Accept
i_{57}	1.5	0.75	18.56	Reject	-	Reject
i_{58}	1.5	0.73	3.51	New round	**Accept**	**Reject**
i_{59}	1.58	0.66	0	Accept	-	Accept
	1.7	0.81	0	Accept	-	Accept

(*continued on next page*)

Table 7 (*continued*)

Indicator	$\overline{X}$	δ	c^*	Delphi (round 1)	Delphi (round 2)	CMCC proposal
i_{60}						
i_{61}	1.39	0.66	0	Accept	-	Accept
i_{62}	1.52	0.76	0	Accept	-	Accept
i_{63}	1.5	0.7	13.57	New round	Reject	Reject
i_{64}	1.44	0.63	4.96	New round	Reject	Reject
i_{65}	1.33	0.82	0	Accept	-	Accept
i_{66}	1.44	0.67	4.52	New round	Reject	Reject
i_{67}	1.28	0.64	5.99	New round	**Accept**	**Reject**
i_{68}	1.58	0.79	0	Accept	-	Accept
i_{69}	1.5	0.8	23.54	Reject	-	Reject
i_{70}	1.5	0.62	32.62	Reject	-	Reject
i_{71}	1.49	0.71	4.76	New round	Reject	Reject
i_{72}	1.5	0.67	7.52	Reject	-	Reject
i_{73}	1.36	0.7	0	Accept	-	Accept
i_{74}	1.52	0.8	0	Accept	-	Accept
i_{75}	1.76	0.75	0	Accept	-	Accept
i_{76}	1.58	0.79	0	Accept	-	Accept
i_{77}	1.5	0.67	10.56	Reject	-	Reject
i_{78}	1.50	0.7	4.51	New round	**Accept**	**Reject**
i_{79}	1.48	0.62	0	Accept	-	Accept
i_{80}	1.44	0.67	5.52	Reject	-	Reject
i_{81}	1.64	0.84	0	New round	Accept	Accept
i_{82}	1.73	0.88	5.22	New round	Reject	Reject
i_{83}	1.5	0.68	11.56	Reject	-	Reject

Table 8
Comparison accepted indicators with respect to the first round.

Approach	Number of accepted indicators
Delphi (round 1)	38
Delphi (round 2)	+8
CMCC proposal	46

Table 9
Global comparison with Delphi methodology.

	Match	False positive	False negative
CMCC proposal	75	0	8

Table 10
Total cost of false negative indicators.

Indicator	c
i_8 proposal	12.85
i_{25} proposal	18.54
i_{28} proposal	25.57
i_{48} proposal	11.27
i_{54} proposal	3.51
i_{58} proposal	3.51
i_{67} proposal	5.99
i_{78} proposal	4.51

solution. Therefore, the study and application of these LSGDM methods for measuring CE has led us to believe that they are useful and promising tools, according to the results obtained in our study. Hence, this study opens up a new line of research focusing on facilitating the measurement of the CE, and creates a useful measurement scale for the CE scenario. In comparison with previous methodologies, such as the Delphi technique, and in answer to our first research question, we can observe that LSGDM is faster, more efficient, less expensive and presents less limitations.

Throughout this article, the CE measurement scale applied to the construction sector (Núñez-Cacho et al., 2018b), which is based on the e-Delphi methodology, has been compared with an alternative proposal to reach an agreement using a CRP, which is based on the novel CMCC model for LSGDM (Labella et al., 2020). In this method, experts only state their preferences once, so there is no need for multiple rounds of review. By applying the Delphi technique, the research team performs multiple rounds of review with time intervals derived from the response time of the experts and the treatment of the data in each of the rounds. This is a complex and expensive process that involves the constant participation of experts, and depends on their availability and involvement in order to obtain results. Thus, (Núñez-Cacho et al., 2018b) mentions that the process began in the first quarter of 2017 and ended in the last quarter of the same year. On the contrary, our proposal based on CMCC for LSGDM does not require the development of multiple consultation rounds, the results are obtained in a much shorter period of time, and in our answer we observe that similar results are obtained.

On the other hand, the LSGDM based on the CMCC model also considers a minimum acceptable agreement among experts to reach the consensus, as well as the distance between the experts' opinions and the collective one, which is used in other methods. In this way, a consensus solution is achieved in a way that other applied techniques do not allow. Another advantage of the proposed method is that since only a single data collection is carried out, there is no risk of experts involved abandoning of the process, nor are there any interpretation biases introduced by the experts concerning the results that are communicated between them. Finally, we refer to the cost savings due to the reduction of the iterations that are carried out. The fact that the method does not require successive rounds allows the cost of obtaining the information to be reduced, so its implementation will improve the results of the organizations. This answers our second research question and allows us to establish the superiority of the method over other previously employed methods.

7. Conclusions

CE is a paradigm shift, and we need to understand and measure the transition to this new business model. To be competitive in today's business world, many companies need to migrate to a CE in order to be sustainable in the long term. On the other hand, the CE is also being promoted by top-level organizations and governments that demand that organizations reflect their position with regard to the CE. As it is a recent paradigm, there are very few scales with which to measure the rate of adoption of the CE by organizations.

In this context, our objective is to provide reliable methodologies to develop and verify these measurement scales. The CMCC model for large scale group decision making is presented in this article as being a reliable method that can replace others, such as the Delphi technique, due to following advantages: i) its capacity to measure the difficulty of reaching an agreement by determining the cost value, which usually refers to the conflict sorrounding an indicator, ii) its time cost, which is quite a lot shorter than other methods that require long processes with multiple iterations that take place over time, CMCC can provide reliable results in much shorter time periods, iii) another important advantage is the method's simplicity, experts do not have to interpret results round after round as they do in Delphi, which leads to high panel abandonment rates; thus CMCC can be applied to large number of experts.

On the other hand, the proposed method also presents some limitations: (i) the impossibility of simulating how experts will behave when they face changes being made to their preferences, and (ii) an excessive cost of time and resources in LSGDM problems with thousands of experts. These limitations can be addressed in future research, for instance, (i) by including a behavior simulation pattern within the CMCC model and (ii) by adapting the non-linear CMCC model used in this proposal to a linear programming model.

There are also several challenges about the application of CMCC LSGDM models to the measurement of the CE that can be addressed in future work, such as i) optimizing the cost value threshold in each problem so as to deal with the acceptance/rejection of indicators and ii) studying the integration of fuzzy methodologies in order to deal with the thresholds of rejection and acceptance in a more flexible way.

CRediT authorship contribution statement

Rosa M. Rodríguez: Writing – original draft, Writing – review & editing, Investigation. **Álvaro Labella:** Writing – original draft, Software, Validation, Visualization. **Pedro Nuñez-Cacho:** Writing – original draft, Writing – review & editing, Formal analysis. **Valentin Molina-Moreno:** Investigation, Methodology, Supervision. **Luis Martínez:** Conceptualization, Methodology, Formal analysis, Supervision, Project administration, Funding acquisition.

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