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Finding Effective Factor for Circular Economy using Uncertain MCDM Approach

Aditi Biswas[1] Kamal Hossain Gazi[2] Sankar Prasad Mondal[2,*]

[1] Department of Basic Science and Humanities, Greater Kolkata College of Engineering & Management, West Bengal, India

[2] Department of Applied Mathematics, Maulana Abul Kalam Azad University of Technology, West Bengal, India

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ABSTRACT

This study investigates the interrelationships among key criteria that support the adoption and implementation of circular economy practices under uncertainty. Five criteria are considered: sustainability, resource management, product lifespan, collaboration and partnerships, and technology and innovation. Because the influence among these criteria may be difficult to express through precise numerical judgments, an interval-valued Decision-Making Trial and Evaluation Laboratory (DEMATEL) framework is employed to represent expert assessments and preserve uncertainty during the evaluation process. Linguistic evaluations provided by two decision-makers are transformed into interval numbers and aggregated to construct the direct-relation matrix. The subsequent DEMATEL procedure is used to derive the total-relation matrix, prominence and relation measures, and threshold values that describe both the overall importance of each criterion and its causal role within the system. The results indicate that Product Lifespan has the strongest overall relationship with the remaining circular economy criteria, whereas Collaboration and Partnerships exhibits the lowest overall relation. The cause-effect analysis further classifies Collaboration and Partnerships and Technology and Innovation as causal or dispatcher criteria, while Sustainability, Resource Management, and Product Lifespan are identified as effect or receiver criteria. A scatter-based representation is additionally used to visualize the dependency structure and the relevant relationships among the criteria. The proposed interval-valued DEMATEL analysis therefore provides a transparent way to identify influential circular economy factors when expert information is imprecise. The findings can support decision-makers in prioritizing interconnected actions for circular economy development while explicitly accounting for uncertainty in expert judgments.

1. Introduction

The circular economy (CE) [1, 2] is a revolutionary economic framework intended to optimise resources efficiency, minimize waste and enhance sustainability by prolonging the lifespan of products' materials. CE can focus on recycling, reusing and recovering resources, contrary to the conventional linear "take-make-dispose" system.

In the integration of decision-making into CE [3], unpredictability is created for some criteria like market dynamics, variability in material flows and stakeholder desires. Multi-criteria decision-making

*Corresponding author.
E-mail address: sankar.res07@gmail.com

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(MCDM) processes deal with this complicated situation by considering different conflicting criteria concurrently. An inquisitive MCDM procedure makes use of tools like interval numbers [4], fuzzy numbers [5], neutrosophic sets [6] or probabilistic linguistic sets [7] models to manage the imprecision and uncertainty and enable a sturdy system to make decisions in Circular Economy execution.

1.1 Circular economy and its need

The circular economy [8, 9] is a unique economic model aimed at getting rid of waste [10] and encouraging the ongoing exploitation of resources [11]. The circular economy places more focus on designing products for adaptability, reuse, remanufacturing and recycling than the conventional linear economy, which follows a ”take-make-dispose” process [12, 13]. It eliminates resource extraction, minimizes environmental harm and cultivates economic resilience by structuring closed-loop systems [14]. A circular economy is critical to ensure sustainable development, reduce ecological impact, and promote a healthier, more equitable future [15] for all because the entire world deals with some critical issues like resource depletion, climate change, mounting waste, etc.

The circular economy transforms the economy By moving away from a wasteful, linear model to one that highlights resource efficiency, sustainability and regeneration. It decreases pollution and waste, lowers dependence on finite resources and encourages innovation in different fields like recycling, product design and renewable energy. This transition yields new green jobs, builds economic resilience and coordinating development with environmental and social wellness and good health, paving the way for a more sustainable and equitable economic system.

1.2 MCDM method for modeling real world problems

Multi-criteria decision-making (MCDM) methodologies [16] are solid tools for handling real-world problems that involve analyzing and choosing among all alternatives based on multiple, often reversing criteria. These techniques help decision-makers systematically analyze the analyse difficult situations, prioritize objectives and balance trade-offs. Techniques like the Analytic Hierarchy Process (AHP) [17], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [18] and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [19] are commonly used to model problems in real fields like environmental management, urban planning, business strategy etc. By incorporating diverse stakeholder viewpoints and quantitative data, MCDM processes give structured, transparent and rational solutions to tough decision-making challenges. Now, we give a brief summary of some significant research work for real-world problems with the MCDM method in Table 1.

1.3 Uncertainty in MCDM methods

Unpredictability in Multi-Criteria Decision-Making (MCDM) methodology appears from the information that is incomplete, imprecise or subjective about criteria weights, preferences or alternatives. This ambiguity may originate from various ambiguous data, human judgment variability, or uncertain external factors. Addressing it requires strong technologies, i.e., fuzzy logic [34], interval analysis [17] or probabilistic models [7], which allow for more versatile representations of preferences and criteria. These adaptations raise the reliability and credibility of MCDM results, ensuring more informed and resilient decision-making in complex, real-world circumstances with the help of explicit accounting for uncertainty. Now, we describe some DEMATEL works in an ambiguous or uncertain environment in Table 2.

1.4 Structure of this study

The structure of this research is presented here. The introduction and literature survey of finding the most important criteria for the circular economy are details discussed in Section 1. Then, the preliminaries of mathematical tools, namely interval number with optimization techniques, namely the DEMATEL method, are analysed in Section 2. The criteria selection procedure and a short discussion

Table 1
Some real-world problem on MCDM-based optimization studies

Authors	Year	MCDM methods	Application Area
[20] Morote, A. N. et al.	2011	AHP	Application in power production system.
[21] Emovon, I. et al.	2020	TOPSIS	Analysis of materials for economic production.
[22] Saraji, M. K. et al.	2021	SWARA, CRITIC & COPRAS	Computing the obstacles to designing business model innovation for sustainability.
[18] Miç, P. et al.	2021	TOPSIS, WASPAS & MULTIMOORA	Proper site selection of university.
[23] Nithyanandham, D. et al.	2021	DEMATEL	Structuring DEMATEL methodology under bipolar uncertain environment.
[24] Kashyap, A. et al.	2022	DEMATEL	Determining the barriers to the implementation of circularity in the aluminium industry.
[25] Mishra, A. R. et al.	2022	COPRAS	Application in considering the desalination technology.
[26] Ahmadsaraei, M. S. et al.	2022	Delphi, CRITIC & COPRAS	Application on sustainable supply chain risk in the food packaging industry.
[27] Nyimbili, P. H. et al.	2023	DEMATEL	Application to analysis of emergency services and urban fire.
[16] Gazi, K. H. et al.	2024	Entropy & VIKOR	Location selection for hospital in Saudi Arabia.
[17] Mandal, S. et al.	2024	AHP & TOPSIS	Choosing the best Ph.D supervisor.
[28] Momena, A. F. et al.	2024	CRITIC & MULTIMOORA	Analysis the challenges of supply chain companies.
[29] Adhikari, D. et al.	2024	Entropy & VIKOR	Ranking of states in India based on women empowerment.
[30] Momena, A. F. et al.	2024	Entropy, WASPAS & CoCoSo	Analysis the adaptation challenges of Edge computing model in an educational institute.
[31] Biswas, A. et al.	2025	Entropy & WASPAS	Site selection for girls hostel in a university campus.
[32] Gazi, K. H. et al.	2025	DEMATEL	Determine the effective factor for women in sport sector.
[33] Biswas, A. et al.	2025	AHP & TOPSIS	Site selection for restaurant beside highway.

Table 2
Some real-world application of DEMATEL method in uncertain environment

Authors	Year	Uncertainty	Application Area
[23] Nithyanandham, D. et al.	2021	Bipolar fuzzy graph	Structuring DEMATEL methodology under bipolar uncertain environment.
[27] Nyimbili, P. H. et al.	2023	Linguistic term	Application to analysis of emergency services and urban fire.
[35] Šmidovnik, T. et al.	2023	Triangular fuzzy number	Solve the convergence problem.
[36] Eti, S. et al.	2023	T-Spherical fuzzy sets	Determine the efficiency of the solar panels for sustainability.
[37] Çelik, M. T. et al.	2023	Triangular fuzzy number	Analysis the productivity of the tempered glass.
[38] Xue, P. et al.	2024	Pentagonal fuzzy numbers	Analysis the imported criteria on flood vulnerability assessment.
[32] Gazi, K. H. et al.	2025	Pentagonal fuzzy number	Determine the effective factor for women in the sports sector.

on it are covered in Section 3. Further, model formulation and data collection process are described in Section 4. The numerical simulation and results are discussed in Section 5. Finally, the conclusion and future research road-maps are mentioned in Section 6.

2. Optimization Technique with Mathematical Tool

This section discusses the interval numbers and their properties in detail. Further, the mathematical procedure of the decision-making trial and evaluation laboratory (DEMATEL) method is presented here and integrated with the interval numbers to incorporate uncertainty and vagueness.

2.1 Preliminaries of Interval Numbers as Mathematical Tool

Interval numbers are fully covered in detail in this section. These are a little different from crisp arithmetic. The research papers by Guerra, M. L. et al. [39] and Quevedo J. R. N. [40], respectively, specifically discuss mathematical operations on intervals.

Definition 1. *Let us choose, $\mathscr{I} = [p^l, p^r]$ be an interval where $p^l \leq p^r$. Then, we evaluate the middle point value of this selected interval is as described as follows,*

$$\overline{p} = \frac{p^r + p^l}{2} \text{ and } \widehat{p} = \frac{p^r - p^l}{2} \tag{1}$$

From Equation (1),we can write the interval $\mathscr{I}$ as bellow,

$$p^l = \overline{p} - \widehat{p} \text{ and } p^r = \overline{p} + \widehat{p} \tag{2}$$

So,

$$\mathscr{I} = [p^l, p^r] = [\overline{p} - \widehat{p}, \overline{p} + \widehat{p}] \tag{3}$$

Moreover, the interval can also be written as follows: $\mathscr{I} = [p^l, p^r] = (\overline{p}; \widehat{p})$. The mathematical representation of the set of all real intervals is $\mathbb{IR}$ and simply $\mathbb{I}$.

Definition 2. *Let us choose, $\mathscr{I} = [-p^l, -p^r]$ where $-p^l \leq -p^r$ or $\mathscr{I} = [-p^l, p^r]$ where $-p^l \leq p^r$ or $\mathscr{I} = [0, p^r]$ where $0 \leq p^r$ or $\mathscr{I} = [-p^l, 0]$ where $p^l \leq 0$ be an interval. Then, we evaluate the middle point value of this selected interval is as described as follows,*

$$\overline{p} = \frac{p^l + p^r}{2} \text{ and } |\widehat{p}| = \left| \frac{p^l - p^r}{2} \right| \tag{4}$$

From Equation (4),we can represent the interval $\mathscr{I}$ as follows,

$$p^l = \overline{p} - |\widehat{p}| \text{ and } p^r = \overline{p} + |\widehat{p}| \tag{5}$$

So,

$$\mathscr{I} = [p^l, p^r] = [\overline{p} - |\widehat{p}|, \overline{p} + |\widehat{p}|] \tag{6}$$

Furthermore, the interval can also be presented as, $\mathscr{I} = [p^l, p^r] = (\overline{p}; |\widehat{p}|)$. And the mathematical structure of the set of all real intervals is $\mathbb{IR}$ and simply $\mathbb{I}$.

Example 1. *Consider $\mathscr{J} = [2, 7]$ be an interval where 2 be lower and 7 be upper bounds. The interval number $\mathscr{J}$, can be represent as $\overline{p} = \frac{p^r+p^l}{2} = \frac{7+2}{2} = 4.5$ and $\widehat{p} = \frac{p^r-p^l}{2} = \frac{7-2}{2} = 2.5$ then*

$$\mathscr{J} = [p^l, p^r] = (\overline{p}; \widehat{p}) = (4.5; 2.5) \tag{7}$$

2.1.1 Arithmetic Operation on Interval Numbers

The arithmetic operations on interval numbers are discussed here. The operations on interval numbers are slightly different from crisp numbers since, in interval numbers, the upper bound is always greater than or equal to the lower bound $(p^r \geq p^l)$. The arithmetic operations on interval numbers are performed as follows:

Consider that, $\mathscr{A} = [x^l, x^r] = (\overline{x}; \widehat{x})$ and $\mathscr{B} = [y^l, y^r] = (\overline{y}; \widehat{y})$. Here, $\overline{x} = \frac{x^l+x^r}{2}$, $\widehat{c} = \frac{x^l-x^r}{2}$, $\overline{y} = \frac{y^r+y^l}{2}$ and $\widehat{d} = \frac{y^r-y^l}{2}$. Therefore, the initial arithmetic operations on intervals are described as,

(a) **Addition of two intervals $\mathscr{A}$ and $\mathscr{B}$:**

$$\mathscr{A} + \mathscr{B} = [x^l, x^r] + [y^l, y^r] = [x^l + y^l, x^r + y^r] = (\overline{x} + \overline{y}; \widehat{x} + \widehat{y}) \tag{8}$$

(b) **Subtraction of two intervals $\mathscr{A}$ and $\mathscr{B}$:**

$$\mathscr{A} - \mathscr{B} = [x^l, x^r] - [y^l, y^r] = [x^l - y^l, x^r - y^r] = (\overline{x} - \overline{y}; \widehat{x} - \widehat{y}) \tag{9}$$

(c) **Scalar multiplication of the interval $\mathscr{A}$:**

$$\begin{aligned}\lambda\mathscr{A} = \lambda \times \mathscr{A} = \lambda \times [x^l, x^r] &= \begin{cases} [\lambda x^l, \lambda x^r] & ;\text{ if } \lambda \geq 0 \\ [\lambda x^r, \lambda x^l] & ;\text{ if } \lambda < 0 \end{cases} \\ &= (\overline{x}; |\lambda|\widehat{x})\end{aligned} \tag{10}$$

where λ is a scalar number.

(d) **Multiplication of two intervals $\mathscr{A}$ and $\mathscr{B}$:**

$$\mathscr{A} \times \mathscr{B} = [x^l, x^r] \times [y^l, y^r] = [z^l, z^r] = (\overline{z}; \widehat{z}) \tag{11}$$

where $z^l = \min\{x^l y^l, x^l y^r, x^r y^l, x^r y^r\}$ and $z^r = \max\{x^l y^l, x^l y^r, x^r y^l, x^r y^r\}$, $\overline{z} = \frac{z^r+z^l}{2}$ and $\widehat{z} = \frac{z^r-z^l}{2}$, respectively.

(e) **Division of two intervals $\mathscr{A}$ and $\mathscr{B}$:**

$$\mathscr{A} \div \mathscr{B} = [x^l, x^r] \div [y^l, y^r] = [z^l, z^r] = (\overline{z}; \widehat{z}) \tag{12}$$

where $z^l = \min\{\frac{x^l}{y^l}, \frac{x^l}{y^r}, \frac{x^r}{y^l}, \frac{x^r}{y^r}\}$ and $z^l = \max\{\frac{x^l}{y^l}, \frac{x^l}{y^r}, \frac{x^r}{y^l}, \frac{x^r}{y^r}\}$, $\overline{z} = \frac{z^r+z^l}{2}$ and $\widehat{z} = \frac{z^r-z^l}{2}$, particularly.

The division of two intervals is possible only when 0 not in the second interval $\mathscr{B}$, i.e., $o \notin [y^l, y^r] (= \mathscr{B})$.

2.1.2 Crispification of Interval Number

This section describes the crispification process of the interval-valued numbers. Since there is no order relation between the interval numbers, then for utilized in optimization technique we crispificated the interval number in a scientific way. The crispification of interval numbers is defined as follows:

Definition 3. *Let us choose, $\mathscr{I} = [p^l, p^r]$ be an interval where $p^l \leq p^r$. If γ and δ be two arbitrary natural numbers. Then, the Crispified value $(\mathcal{C}(\mathscr{I}))$ of $\mathscr{I}$ is expressed as below,*

$$\mathcal{C}(\mathscr{I}) = \frac{\gamma p^l + \delta p^r}{\gamma + \delta} \tag{13}$$

Case 1: (Both numbers in an interval are positive)

Here, three conditions are considered to find the Crispified value $(\mathcal{C}(\mathscr{I}))$ of $\mathscr{I}$, s.t.,

a. If $\gamma < \delta$, then the value of $\mathcal{C}(\mathscr{I})$, that is expressed in Equation (13) will be considered. Here, the resulting number will be close to the right-hand number of the considered interval.

b. If $\delta < \gamma$, then the value of $\mathcal{C}(\mathscr{I})$, that is expressed in Equation (13) will be considered. Here, the resulting number will be close to the left-hand number of the considered interval.

c. If $\gamma = \delta$, then the value of $\mathcal{C}(\mathscr{I})$, that is expressed in Equation (13) will be considered. The resulting number will be the middle number of the considered interval.

Case 2: (Both numbers in an interval are negative)
In this case, the choosen interval is $\mathscr{I} = [-p^l, -p^r]$ where $-p^l \leq -p^r$. We can evaluate the crispified value from the Equation (13). And the three conditions that have already been considered in Case 1, when re-considered in Case 2, have almost the same resulting crispified values.

Case 3: (First number is negative and the another number is positive in an interval)
If the considered interval is $\mathscr{I} = [-p^l, p^r]$ where $-p^l \leq p^r$. We can calculate the crispified value from the Equation (13). Then, the three conditions that have already been considered in Case 1 and 2 when re-considered in Case 3, have the similar resulting crispified values. When $\gamma < \delta$, $\delta < \gamma$ and $\gamma = \delta$ occur, then the required number will be close to the right-hand, left-hand and middle number of the considered interval.

Case 4: (First number is zero and the another number is positive in an interval)
When the selected interval is $\mathscr{I} = [0, p^r]$ where $0 \leq p^r$. We can evaluate the crispified value from the Equation (13). In this paper, the three conditions that have already been considered in Case 1,2 and 3 when re-considered in Case 4, have the similar resulting crispified values. When $\gamma < \delta$, $\delta < \gamma$ and $\gamma = \delta$ occur, then the required number will be close to the right-hand, left-hand and middle number of the considered interval, particularly.

Case 5: (First number is negative and the another number is zero in an interval)
Let, the choosed interval is $\mathscr{I} = [-p^l, 0]$ where $-p^l \leq 0$. We can compute the crispified value from the Equation (13). Here, the three conditions that have already been considered in Case 1,2,3 and 4 when re-considered in Case 5, have the similar resulting crispified values. When $\gamma < \delta$, $\delta < \gamma$ and $\gamma = \delta$ occur, then the required number will be close to the right-hand, left-hand and the middle number of the considered interval separately.

Example 2. *Let, $\mathscr{I} = [2, 8]$ and γ and δ be two arbitrary crisp numbers. Therefore, the Crispified value of $\mathscr{I}$ is designed as below,*

$$\mathcal{C}(\mathscr{I}) = \frac{2\gamma + 8\delta}{\gamma + \delta} \tag{14}$$

Here, if $\gamma = \delta = 2$, then the Crispified value of $\mathscr{I}$, denoted as $\mathcal{C}(\mathscr{I})$ is,

$$\begin{aligned} \mathcal{C}(\mathscr{I}) =& \frac{(2 \times 2) + (8 \times 2)}{2 + 2} \\ =& \frac{4 + 16}{4} \\ =& \frac{20}{4} \\ =& 5 \end{aligned} \tag{15}$$

or, If $\gamma = \delta = 5$, then the value of $\mathcal{C}(\mathscr{I})$ is,

$$\begin{aligned}\mathcal{C}(\mathscr{I}) =& \frac{(2 \times 5) + (8 \times 5)}{5+5}\\ =& \frac{10+40}{10}\\ =& \frac{50}{10}\\ =& 5\end{aligned} \tag{16}$$

Here, the resulting number is 5, which is the middle number in both Equations (15) *and* (16)*.*

Example 3. *Let, $\mathscr{I} = [-8, -2]$ and γ and δ be two arbitrary crisp numbers. Therefore, the Crispified value of $\mathscr{I}$ is designed as below,*

$$\mathcal{C}(\mathscr{I}) = \frac{(-8)\gamma + (-2)\delta}{\gamma + \delta} \tag{17}$$

If $\delta = 2$ and $\gamma = 5$ where, $\delta < \gamma$. Therefore, the Crispified value of $\mathscr{I}$, defined as $\mathcal{C}(\mathscr{I})$ is,

$$\begin{aligned}\mathcal{C}(\mathscr{I}) =& \frac{((-8) \times 5) + ((-2) \times 2)}{5+2}\\ =& \frac{-40-4}{7}\\ =& \frac{-44}{7}\\ =& -6.29\end{aligned} \tag{18}$$

Here, the resulting number is -6.29, which is close to the left-hand number of the chosen interval $\mathscr{I} = [-8, -2]$.

Example 4. *Let, $\mathscr{I} = [-2, 8]$ and γ and δ be two arbitrary crisp numbers. Therefore, the Crispified value of $\mathscr{I}$ is designed as below,*

$$\mathcal{C}(\mathscr{I}) = \frac{(-2)\gamma + 8\delta}{\gamma + \delta} \tag{19}$$

If $\gamma = 2$ and $\delta = 5$ where, $\gamma < \delta$. So, the Crispified value of $\mathscr{I}$, expressed as $\mathcal{C}(\mathscr{I})$ is,

$$\begin{aligned}\mathcal{C}(\mathscr{I}) =& \frac{((-2) \times 2) + (8 \times 5)}{2+5}\\ =& \frac{-4+40}{7}\\ =& \frac{36}{7}\\ =& 5.14\end{aligned} \tag{20}$$

where the resulting number is 5.14, which is close to the right-hand number of the considered interval $\mathscr{I} = [-2, 8]$.

2.2 MCDM Methodology: Decision Making Trial and Evaluation Laboratory (DEMATEL)

The weighted MCDM method, named the decision making trial and evaluation laboratory (DEMATEL) technique, is described in the interval numbers in this portion. This process was first proposed by Tzeng, G. et al. in 2007 [41]. This approach uses an impact relationship diagram to identify the key variables of a complicated system and convert the interactions between criteria into the cause and effect group.

The DEMATEL methodology uses in vast areas in real life, and here we show some utilization of this method, such as in the industrial engineering field with objective data and subjective viewpoints [42], management of supply chain risk [43], the criteria that controlling air traffic performance [44], analysis of emergency services and urban fire [27], web-advertising impact on structural equation modelling (SEM) [45], the impact of online programs [41], investigating the quality of healthcare services [46], choosing the operator for a mobile banking service [47] and many more. In this paper, we use the DEMATEL process in interval numbers. The graphical flowchart of the DEMATEL process is displayed in Figure 1. Here, Table 4 estimates the correlation between the uth with vth criterion, as measured by the comparison scale, where $u, v = 1, 2, \ldots, t$. Further, f number of decision makers (DMs) gave their sensible and valuable decision and this is formulated by $\delta^t h$ decision maker where $\delta = 1, 2, \ldots, f$. Now, the steps of the DEMATET method are executed as below,

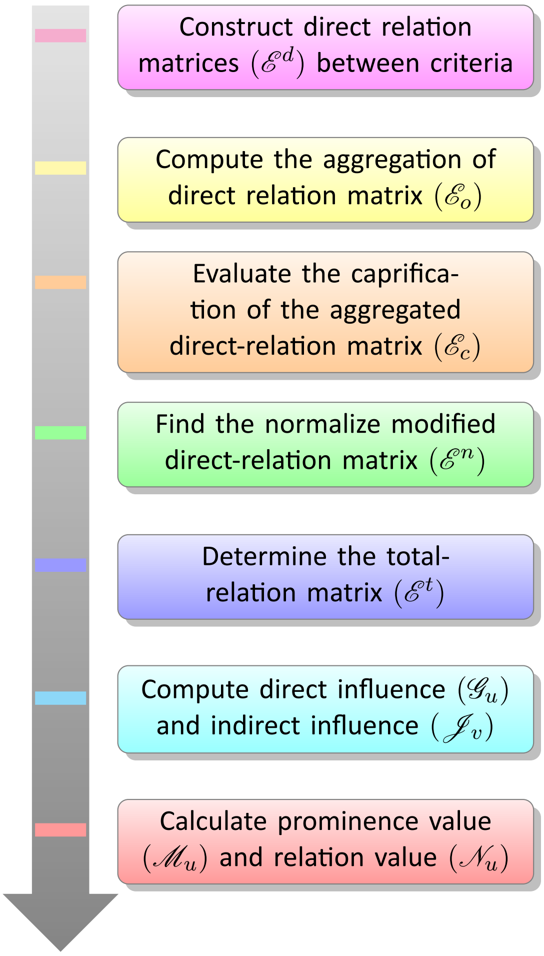

Fig. 1. An organisational hierarchy of the DEMATEL process

a. **Formulation of the direct relation matrix** $(\mathscr{E}_d)$**:**
Each and every decision maker gives their wise decision in linguistic terms and then, which are converted to interval numbers. There are f direct relation matrices $(\mathscr{E}_\delta)$ formulated with $t \times t$

order. The dth direct relation matrix $(\mathscr{E}_\delta)$ structured as

$$\mathscr{E}_\delta = \begin{bmatrix} (\mathscr{H}_{11})_\delta & (\mathscr{H}_{12})_\delta & \dots & (\mathscr{H}_{1v})_\delta & \dots & (\mathscr{H}_{1t})_\delta \\ (\mathscr{H}_{21})_\delta & (\mathscr{H}_{22})_\delta & \dots & (\mathscr{H}_{2v})_\delta & \dots & (\mathscr{H}_{2t})_\delta \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\mathscr{H}_{u1})_\delta & (\mathscr{H}_{u2})_\delta & \dots & (\mathscr{H}_{uv})_\delta & \dots & (\mathscr{H}_{ut})_\delta \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ (\mathscr{H}_{t1})_\delta & (\mathscr{H}_{t2})_\delta & \dots & (\mathscr{H}_{tv})_\delta & \dots & (\mathscr{H}_{tt})_\delta \end{bmatrix}_{t\times t} \tag{21}$$

So, by δth DM, every entry represents the ratings of vth criteria with uth criteria. The Equation (21) can also be presented with interval numbers as follows,

$$(\mathscr{H}_{uv})_\delta = \left[\left\{(p^l_{1uv})_\delta, (p^l_{2uv})_\delta, (p^l_{3uv})_\delta, \dots, (p^l_{nuv})_\delta\right\}, \left\{(p^r_{1uv})_\delta, (p^r_{2uv})_\delta, (p^r_{3uv})_\delta, \dots, (p^r_{nuv})_\delta\right\}\right] \tag{22}$$

b. Aggregation of direct relation matrices $(\mathscr{E}_o)$:
For further assessment, all f number of direct matrices $(\mathscr{E}_\delta)$ convert into one direct relation matrix $(\mathscr{E}_o)$ where $\delta = 1, 2, \dots, f$. Combine the every uvth entry of $(\mathscr{H}_{uv})$ and accumulate it with one direct relation matrix, which is denoted by $(\mathscr{E}_o)$ in Equation (23), s.t.,

$$\varrho_{(\mathscr{H}_{uv})_\delta} = \left[\left\{\frac{(p^l_{1uv})_\delta + (p^l_{2uv})_\delta + \cdots + (p^l_{nuv})_\delta}{n}\right\}, \left\{\frac{(p^r_{1uv})_\delta + (p^r_{2uv})_\delta + \cdots + (p^r_{nuv})_\delta}{n}\right\}\right] \tag{23}$$

Then, the direct relation matrix is,

$$\mathscr{E}_o = [\mathscr{H}_{uv}]_{t\times t} = \begin{bmatrix} \mathscr{H}_{11} & \mathscr{H}_{12} & \dots & \mathscr{H}_{1v} & \dots & \mathscr{H}_{1t} \\ \mathscr{H}_{21} & \mathscr{H}_{22} & \dots & \mathscr{H}_{2v} & \dots & \mathscr{H}_{2t} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathscr{H}_{u1} & \mathscr{H}_{u2} & \dots & \mathscr{H}_{uv} & \dots & \mathscr{H}_{ut} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathscr{H}_{t1} & \mathscr{H}_{t2} & \dots & \mathscr{H}_{tv} & \dots & \mathscr{H}_{tt} \end{bmatrix}_{t\times t} \tag{24}$$

c. Crispification the aggregated direct-relation matrix $(\mathscr{E}_c)$:
Evaluate the crispified value of the above aggregated direct-relation matrix $(\mathscr{E}_c)$ with the help of crispified value of every entry of the aggregated direct-relation matrix $(\mathscr{E}_o)$ with the already described formula of crispification in Equation (13). Now, the crispified aggregated direct-relation matrix $(\mathscr{E}_c)$ is,

$$\mathscr{E}_c = [\mathscr{H}_{uv}]_{t\times t} \tag{25}$$

d. Normalize the modified direct-relation matrix $(\mathscr{E}_n)$:
In this step, we normalize the modified direct-relation matrix $\mathscr{E}_c$ and structure the normalizing direct-relation matrix $(\mathscr{E}_n)$, i.e.,

$$\mathscr{E}_n = [(\mathscr{H}_{uv})_n]_{t\times t} = \left[\frac{\mathscr{H}_{uv}}{\max\limits_{1\le u\le t}\left\{\sum_{v=1}^{t}\mathscr{H}_{uv}\right\}}\right]_{t\times t} \tag{26}$$

where $u, v = 1, 2, \dots, t$.

e. Compute the total-relation matrix $(\mathscr{E}_t)$:
From the normalizing direct-relation matrix $(\mathscr{E}_n)$, the total-relation matrix $(\mathscr{E}_t)$ id described as below,

$$\begin{aligned}\mathscr{E}_t &= \lim_{\iota\to\infty}\left\langle \mathscr{E}_n + (\mathscr{E}_n)^2 + (\mathscr{E}_n)^3 + \cdots + (\mathscr{E}_n)^{\chi}\right\rangle \\ \text{or, } \mathscr{E}_t &= \mathscr{E}_n\left(\mathcal{I} - \mathscr{E}_n\right)^{-1} = [\mathscr{D}_{uv}]_{t\times t}\end{aligned} \tag{27}$$

In Equation (27), $\mathscr{D}_{uv}$ is the uvth entry of the total-relation matrix and $\mathcal{I}$ be the identity matrix with $t \times t$ order.

f. Evaluate the direct influence $(\mathscr{G}_u)$ and indirect influence $(\mathscr{J}_v)$ for the criteria:
The sum of uth row entries of the total-relation matrix $(\mathscr{E}_t)$ is denoted as direct influence value, i.e.,

$$\mathscr{G}_u = \sum_{v=1}^{t} \mathscr{D}_{uv} \tag{28}$$

where $u = 1, 2, \ldots, t$.
The sum of vth column entries of this total-relation matrix $(\mathscr{E}_t)$ is known as indirect influence value, i.e.,

$$\mathscr{J}_v = \sum_{u=1}^{t} \mathscr{D}_{uv} \tag{29}$$

where $v = 1, 2, \ldots, t$.

g. Calculate sum values:
From the data collection, causal diagrams are calculated for each criteria. Then, the prominence value $(\mathscr{M}_u)$ of every criteria are lies in the horizontal axis and expressed as,

$$\mathscr{M}_u = \mathscr{G}_u + \mathscr{J}_u = \sum_{v=1}^{t} \mathscr{D}_{uv} + \sum_{v=1}^{t} \mathscr{D}_{vu} \tag{30}$$

and the relation value $(\mathscr{N}_u)$ of every criteria are lies in the vertical axis and determined as,

$$\mathscr{N}_u = \mathscr{G}_u - \mathscr{J}_u = \sum_{v=1}^{t} \mathscr{D}_{uv} - \sum_{v=1}^{t} \mathscr{D}_{vu} \tag{31}$$

where $u, v = 1, 2, \ldots, t$.

h. Analysis the efficient criteria:
In this final step, the prominence value $(\mathscr{M}_u)$ expresses the importance of criteria, that it shows exhibits the degree to which each criterion relates to others. Here, the higher and the lower values of $\mathscr{M}_u$ indicate that the criteria have more relation with other criteria and the criteria have less relation with other criteria, respectively.
On the other hand, the relation value $(\mathscr{N}_u)$ denotes the kind of relation among the criteria. When the value of this is positive $(+ve)$ and negative $(-ve)$, then the criteria belongs to the cause dispatcher or group; that is the uth criteria influence other criteria and the criteria belong to the effect group or receiver, that is uth criteria influenced by the other criteria, respectively. Finally, we can draw the causal diagram in XY plane, based on the $\mathscr{M}_u$ and $\mathscr{N}_n$ values of the criteria, where $u = 1, 2, \ldots, t$. The causal diagram shows the direct and indirect impact of each criteria over the other criteria. Moreover, DMs can establish the threshold value to find the negligible impact of criteria over the rest.

i. Determine the threshold value $(\mathscr{X}^t)$:
The threshold value $(\mathscr{X}^t)$ is evaluated from the total-relation matrix $(\mathscr{E}_t)$, which is evaluated in Equation (27). It is calculated by Equation (32), as follows:

$$\mathscr{X}^t = \frac{\sum_{u=1}^{t} \sum_{v=1}^{t} (\mathcal{X}_{\phi\psi})}{t^2} \tag{32}$$

where $u, v = 1, 2, \ldots, t$.

j. Calculate scatter matrix $(\mathscr{S}^t)$:
The scatter matrix $(\mathscr{S}^t)$ formulate from the total-relation matrix $(\mathscr{E}_t)$ and the threshold value $(\mathscr{X}^t)$ by using Equation (33), as follows:

$$uv^{th} \text{ entry} = \begin{cases} \surd \text{ (i.e., entry is relatable)} & ; \text{if } \mathscr{S}^t \geq \mathscr{D}_{uv} \\ \times \text{ (i.e., entry is not relatable)} & ; \text{if } \mathscr{S}^t < \mathscr{D}_{uv} \end{cases} \tag{33}$$

where $u, v = 1, 2, \ldots, t$. If the uv^{th} entry of the scatter matrix $(\mathscr{S}^t)$ is retable $(\surd)$, then the u^{th} criteria relatable with the v^{th} criteria. Conversely, if the uv^{th} entry of the scatter matrix $(\mathscr{S}^t)$ is not retable $(\times)$, then the u^{th} criteria not relatable with the v^{th} criteria. Additionally, the scatter diagram drowns from the scatter matrix $(\mathscr{S}^t)$ to visualize the relationship graph among the criteria.

3. Criteria Selection

The criteria of a circular economy are very important [1] for creating an infrastructure which is sustainable and resource-efficient. Waste is minimized and resources are preserved by planning for longevity and reusability. Recycling can pledge materials retain their value, reducing environmental impact. Renewable resource use encourages the efficiency of energy and reduces dependence on limited materials. Circular economy models [48, 49, 50, 51] drive innovation and economic development while reducing waste. Balance in the environmental, social and economic areas is ensured by holistic system thinking. Collaboration enhances responsibility and accelerates the adoption of the circular economy system. Briefly, these criteria increase sustainable growth and resilience against resource constraints and environmental glitches. The above criteria are described in detail below, such that,

3.1 Sustainability

Sustainability [52] is a key factor of the circular economy as it signifies that resources are used properly, the waste remains at a minimum, and the environmental effect of people's activities is reduced. In order to preserve ecosystems, conserve natural resources and mitigate climate change, a circular economy fosters sustainable behaviours, such as reuse, recycling and renewable energy. This approach supports longevity and resilience by minimizing dependence on finite resources and structuring closed-loop systems that prioritize regeneration over extraction, ultimately enabling a balanced relationship between economic expansion, social wellness and environmental protection. For more details, we can follow the research works [52, 53, 54, 55].

3.2 Resource Management

Resource management [56] is fundamental thing to the circular economy as it assures the reliable and responsible use of substances throughout their lifecycle, lowering waste and saving natural resources. This can be done by emphasizing methods like sustainable sources, material reuse, waste recycling, and environmentally friendly purchasing. In order to facilitate resilience and sustainable production and consumption, the creation of closed-loop systems, in which resources are continuously in the circular economy, is also made possible. It can construct effective resource management, which is the backbone of a circular economy while maintaining total ecological balance. More studies on resource management describe the following articles [57, 58, 59].

3.3 Product Lifespan

Product lifespan [60] is very important for the circular economy as extending the life of products minimizes the need for newly acquired resource extraction and reduces waste production. Businesses may promote reuse, refurbishment and refurbished manufacturing and by making products designing durable, repairable, and upgradable products. A longer product lifespan improves resource efficiency, diminishes the environmental effect of production and disposal and favours with sustainable consumption practices. This process not only supports the goals of the circular economy but also encourages cost savings, customer loyalty, and a move towards safer economic systems. To know more about product lifespan, follow this [61, 54, 55] articles.

3.4 Collaboration and Partnerships

The circular economy depends on collaboration and partnerships [62] because they empower the sharing of knowledge, resources, and innovations across industries, governments, and communities to develop an effective closed-loop system. Through motivating collaboration amongst the stakeholders, businesses can establish industrial symbiosis, where the waste or byproducts of one process become useful inputs for another product. Partnerships additionally stimulate infrastructure development, align policies, and develop sustainable supply chains for salvaging resources and recycling. This collective effort accelerates the transition to a circular economy by resolving obstacles, venturing solutions and verifying that the advantages of circular practices are distributed equitably across the society. Anyone can follow [62, 63, 64, 65] research paper for more clearance.

3.5 Technology and Innovation

Technology and innovation [66] are vital for promoting the circular economy by enabling efficient resource use, debris reduction, and generating sustainable solutions. Advanced technologies like artificial intelligence (AI), the Internet of Things (IoT), and blockchain enhance resource tracking, optimize supply chains, improve recycling procedures, enhancing materials that are reused and repurposed effectively. In materials science, different innovations, like biodegradable or infinitely recyclable materials, reduce environmental impact and contract new opportunities for environmentally friendly product design. In addition, these advancements not only drive the transition to a circular economy but also constitute new business possibilities, expand fortitude and support the progress of closed-loop systems that connect environmental preservation with economic growth. For more details on technology and innovation, follow this [67, 68, 69] studies.

4. Model Formulation and Data Collection

This portion elaborately provides this study's model formulation and data collection process. Firstly, the proposed research model will be developed, followed by the data assembly process from two decision-makers (DMs).

4.1 Model Formulation

The model of this study is formulated in this section. Interval numbers, which are considered here as the mathematical tool, are discussed in Section 2.1 and the MCDM-based DEMATEL methodology is mentioned in Section 2.2, respectively. The specific discussion on criteria is mentioned in Section 3. According to the perspectives of detailed literature review and decision experts, there are five key criteria for finding valuable criteria in the circular economy. The direct relation matrices $(\mathscr{E}^d)$ with 5×5 order in linguistic terms given by the two DMs using Table 4. The graphical flowchart of the proposed model is presented in Figure 2. Each of those two DMs has expertise, objectivity, and professionalism in their field. They are,

DM1: A professor of a university of Economics department.
DM2: A person who is a social economist.

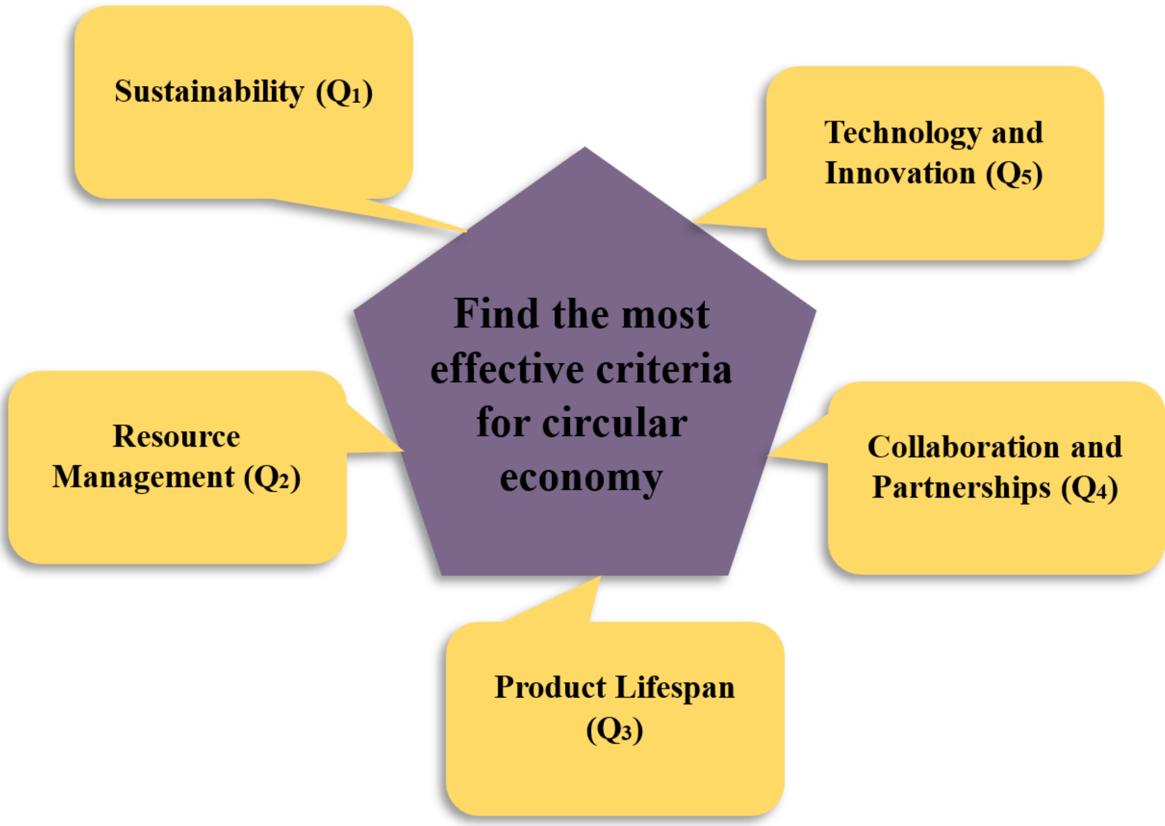

Fig. 2. The hierarchical structure of the suggested model

4.2 Data Collection Procedure

This section explains the data sources and data collection used in this research work. At first, the data are gathered by DMs in linguistic terms that we use it in the direct relation matrices $(\mathscr{E}^d)$ with the help of Table 3 and included in Table 4. Then, the direct relation matrices $(\mathscr{E}^d)$ deciphered into interval numbers using Table 3 and emerged for the DEMATEL method using Section 4.

Table 3
Linguistic term with Interval number and crispified value for direct relation matrix $(\mathscr{E}_d)$

Linguistic Terms	**Interval Number**	**Crispified value**		
		$\gamma = 2, \delta = 5$	$\gamma = 5, \delta = 2$	$\gamma = \delta = 5$
Extremely Importance (EI)	[6,12]	10.29	7.71	9
Highly Importance (HI)	[5,11]	9.29	6.71	8
Very Importance (VI)	[4,10]	8.29	5.71	7
Average Importance (AI)	[3,9]	7.29	4.71	6
Less Importance (LI)	[2,8]	6.29	3.71	5
Below Importance (BI)	[1,7]	5.29	2.71	4
Weekly Importance (WI)	[-3,3]	1.29	-1.29	0

5. Numerical Simulation

The numerical simulation of the most effective criteria for circular economy is determined and the results are analysed here. We consider the DEMATEL methodology (see Section 3.2) as an optimization technique in Interval Numbers (see Section 3.1). Further, consider the Direct relation matrix $(\mathscr{E}^d)$ (in Table 4) as the data source for numerical evaluation.

Table 4
Direct relation matrix ($\mathscr{E}_d$) in linguistic terms of criteria and criteria given by two DMs

	Criteria vs Criteria	Sustainability ($\mathcal{Q}_1$)	Resource Management ($\mathcal{Q}_2$)	Product Lifespan ($\mathcal{Q}_3$)	Collaboration and Partnerships ($\mathcal{Q}_4$)	Technology and Innovation ($\mathcal{Q}_5$)
DM 1	Sustainability ($\mathcal{Q}_1$)	WI	HI	EI	AI	BI
	Resource Management ($\mathcal{Q}_2$)	EI	WI	VI	LI	AI
	Product Lifespan ($\mathcal{Q}_3$)	EI	HI	WI	BI	VI
	Collaboration and Partnerships ($\mathcal{Q}_4$)	BI	LI	AI	WI	HI
	Technology and Innovation ($\mathcal{Q}_5$)	EI	VI	HI	EI	WI
	Criteria vs Criteria	**Sustainability ($\mathcal{Q}_1$)**	**Resource Management ($\mathcal{Q}_2$)**	**Product Lifespan ($\mathcal{Q}_3$)**	**Collaboration and Partnerships ($\mathcal{Q}_4$)**	**Technology and Innovation ($\mathcal{Q}_5$)**
DM 2	Sustainability ($\mathcal{Q}_1$)	WI	VI	HI	LI	BI
	Resource Management ($\mathcal{Q}_2$)	EI	WI	HI	BI	LI
	Product Lifespan ($\mathcal{Q}_3$)	EI	EI	WI	BI	AI
	Collaboration and Partnerships ($\mathcal{Q}_4$)	LI	BI	AI	WI	VI
	Technology and Innovation ($\mathcal{Q}_5$)	HI	VI	VI	HI	WI

The DEMATEL method evaluated the required results as follows: Firstly, construct the direct relation matrix ($\mathscr{E}^d$) by two DMs using Equation (21), shown in Table 2. Then aggregated direct relation matrices ($\mathscr{M}_a$) evaluated by Equation (23). Further, the crispified aggregated direct-relation matrix ($\mathscr{E}_c$) determined by Equation (13) and shown in Table 5. Thereafter, Equation (26) calculated the normalizing modified direct-relation matrix ($\mathscr{E}^n$) in Table 6. Then evaluate the total-relation matrix ($\mathscr{E}^t$) in Table 7 using Equation (27). Finally, the direct influence ($\mathscr{G}_u$), indirect influence ($\mathscr{J}_v$), prominence value ($\mathscr{M}_u$) and relation value ($\mathscr{N}_u$) values for every criteria ($u = 1, 2, \ldots, t$) are calculated by Equations (28), (29), (30) and (31), respectively and shown in Table 8.

Table 5
Crispified the aggregated direct-relation matrix ($\mathscr{E}_c$)

Criteria vs criteria	$\mathcal{Q}_1$	$\mathcal{Q}_2$	$\mathcal{Q}_3$	$\mathcal{Q}_4$	$\mathcal{Q}_5$
Sustainability ($\mathcal{Q}_1$)	0.00	7.50	8.50	5.50	4.00
Resource Management ($\mathcal{Q}_2$)	9.00	0.00	7.50	4.50	5.50
Product Lifespan ($\mathcal{Q}_3$)	9.00	8.50	0.00	4.00	6.50
Collaboration and Partnerships ($\mathcal{Q}_4$)	4.50	4.50	6.00	0.00	7.50
Technology and Innovation ($\mathcal{Q}_5$)	8.50	7.00	7.50	8.50	0.00

Table 8 presented the numerical results of the fuzzy DEMATEL method between criteria of circular emocomy. From the prominence value ($\mathscr{M}_u$) values, we conclude that the degree of the relationship of one particular criterion among the other criteria. For example, the criteria Product Lifespan ($\mathcal{Q}_3$) is the maximum relation with other criteria. Further,Sustainability ($\mathcal{Q}_1$), Resource Management ($\mathcal{Q}_2$) and Technology and Innovation ($\mathcal{Q}_5$) criteria are the second, third and fourth height relation with the

Table 6
Normalizing the modified direct-relation matrix $(\mathscr{E}_n)$

Criteria vs criteria	$\mathcal{Q}_1$	$\mathcal{Q}_2$	$\mathcal{Q}_3$	$\mathcal{Q}_4$	$\mathcal{Q}_5$
Sustainability $(\mathcal{Q}_1)$	0.000	0.242	0.274	0.177	0.129
Resource Management $(\mathcal{Q}_2)$	0.290	0.000	0.242	0.145	0.177
Product Lifespan $(\mathcal{Q}_3)$	0.290	0.274	0.000	0.129	0.210
Collaboration and Partnerships $(\mathcal{Q}_4)$	0.145	0.145	0.194	0.000	0.242
Technology and Innovation $(\mathcal{Q}_5)$	0.274	0.226	0.242	0.274	0.000

Table 7
Total-relation matrix $(\mathscr{E}_t)$

Criteria vs criteria	$\mathcal{Q}_1$	$\mathcal{Q}_2$	$\mathcal{Q}_3$	$\mathcal{Q}_4$	$\mathcal{Q}_5$
Sustainability $(\mathcal{Q}_1)$	1.2401	1.3232	1.4004	1.0649	1.0750
Resource Management $(\mathcal{Q}_2)$	1.5140	1.1717	1.4256	1.0806	1.1409
Product Lifespan $(\mathcal{Q}_3)$	1.5808	1.4474	1.2933	1.1188	1.2122
Collaboration and Partnerships $(\mathcal{Q}_4)$	1.2582	1.1552	1.2414	0.8456	1.0740
Technology and Innovation $(\mathcal{Q}_5)$	1.6835	1.5201	1.6010	1.3127	1.1401

Table 8
Threshold values of the different criteria

Criteria	$\mathscr{G}_u = \sum_{v=1}^{t} \mathscr{D}_{uv}$	$\mathscr{J}_v = \sum_{u=1}^{t} \mathscr{D}_{uv}$	$\mathscr{M}_u = \mathscr{G}_u + \mathscr{J}_u$	$\mathscr{N}_u = \mathscr{G}_u - \mathscr{J}_u$
Sustainability $(\mathcal{Q}_1)$	6.1036	7.2765	13.3801	-1.1729
Resource Management $(\mathcal{Q}_2)$	6.3328	6.6176	12.9503	-0.2848
Product Lifespan $(\mathcal{Q}_3)$	6.6525	6.9617	13.6142	-0.3092
Collaboration and Partnerships $(\mathcal{Q}_4)$	5.5744	5.4227	10.9971	0.1517
Technology and Innovation $(\mathcal{Q}_5)$	7.2574	5.6422	12.8996	1.6152

remaining criteria, respectively. Moreover, Collaboration and Partnerships $(\mathcal{Q}_4)$ criteria is the lowest relation among all the criteria, respectively.

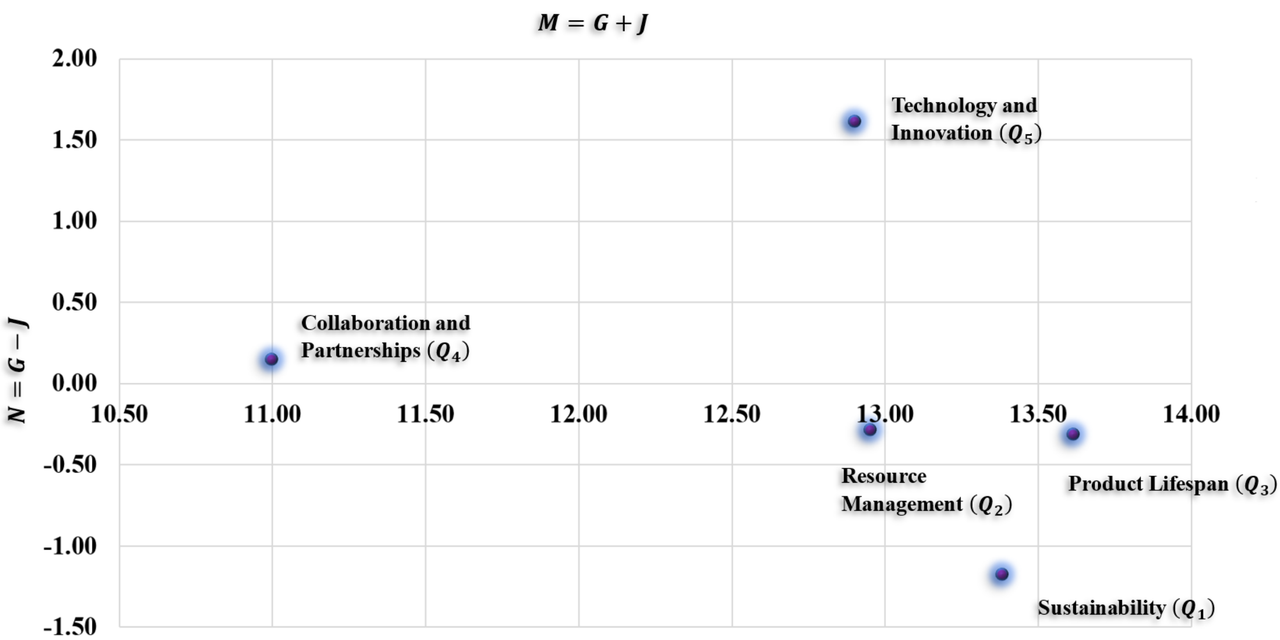

Fig. 3. Causal diagram based on $\mathscr{M}_u$ and $\mathscr{N}_u$ values for every criteria

On the other hand, the relation value $(\mathscr{N}_u)$ values of the criteria are also known from Table 6 and it reveals the kind of relation among the criteria. The relation value $(\mathscr{N}_u)$ values positive $(+ve)$ indicates that the criteria belong to the cause group or dispatcher and negative $(-ve)$ indicates that the criteria belong to the effect group or receiver. For example, Collaboration and Partnerships $(\mathscr{Q}_4)$ and Technology and Innovation $(\mathscr{Q}_5)$ criteria are the cause group or dispatcher and Sustainability $(\mathscr{Q}_1)$, Resource Management $(\mathscr{Q}_2)$ and Product Lifespan $(\mathscr{Q}_3)$ criteria are the effect group or receiver, respectively.

The threshold value $(\mathscr{X}^t)$ of the proposed circular economy model is calculated by Equation (32) and the value is 1.2768. Further, the scatter matrix $(\mathscr{S}^t)$ was evaluated using Equation (33) and shown in Table 9. The scatter diagram drowns using the scatter matrix $(\mathscr{S}^t)$ and is depicted in Figure 4.

Table 9
scatter matrix $(\mathscr{S}^t)$ of proposed DEMATEL model

Criteria	$\mathscr{Q}_1$	$\mathscr{Q}_2$	$\mathscr{Q}_3$	$\mathscr{Q}_4$	$\mathscr{Q}_5$
Sustainability $(\mathscr{Q}_1)$	$\times$	$\surd$	$\surd$	$\times$	$\times$
Resource Management $(\mathscr{Q}_2)$	$\surd$	$\times$	$\surd$	$\times$	$\times$
Product Lifespan $(\mathscr{Q}_3)$	$\surd$	$\surd$	$\surd$	$\times$	$\times$
Collaboration and Partnerships $(\mathscr{Q}_4)$	$\times$	$\times$	$\times$	$\times$	$\times$
Technology and Innovation $(\mathscr{Q}_5)$	$\surd$	$\surd$	$\surd$	$\surd$	$\times$

Remark 1. *From Table 9 and Figure 4, we conclude that the criteria Sustainability $(\mathscr{Q}_1)$ is retable $(\surd)$ with $\mathscr{Q}_2$ and $\mathscr{Q}_3$, the criteria Resource Management $(\mathscr{Q}_2)$ is retable $(\surd)$ with $\mathscr{Q}_1$ and $\mathscr{Q}_3$, the criteria Product Lifespan $(\mathscr{Q}_3)$ is retable $(\surd)$ with $\mathscr{Q}_1$, $\mathscr{Q}_2$ and $\mathscr{Q}_3$ and criteria Technology and Innovation $(\mathscr{Q}_5)$ is retable $(\surd)$ with $\mathscr{Q}_1$, $\mathscr{Q}_2$, $\mathscr{Q}_3$ and $\mathscr{Q}_4$, respectively. Further, the criteria Collaboration and Partnerships $(\mathscr{Q}_4)$ is not retable $(\times)$ with any criteria.*

Fig. 4. Scatter diagram of the scatter matrix $(\mathscr{S}^t)$

6. Conclusion

This study examined the direct and indirect relationships among five interconnected criteria for circular economy implementation: Sustainability $(\mathscr{Q}_1)$, Resource Management $(\mathscr{Q}_2)$, Product Lifespan

$(\mathcal{Q}_3)$, Collaboration and Partnerships $(\mathcal{Q}_4)$, and Technology and Innovation $(\mathcal{Q}_5)$. To represent the uncertainty inherent in expert assessments, linguistic judgments obtained from two decision-makers were converted into interval numbers and processed through an interval-valued DEMATEL framework. This procedure enabled the construction of the direct- and total-relation matrices and the calculation of prominence and relation measures for all criteria. In this way, the analysis identifies not only which criteria are strongly connected with the circular economy system but also whether they primarily act as causal drivers or as receiving criteria influenced by the remaining factors.

The numerical results show that Product Lifespan $(\mathcal{Q}_3)$ has the strongest overall relationship with the other criteria, while Collaboration and Partnerships $(\mathcal{Q}_4)$ has the lowest overall relation. The cause-effect analysis further indicates that Collaboration and Partnerships $(\mathcal{Q}_4)$ and Technology and Innovation $(\mathcal{Q}_5)$ belong to the cause or dispatcher group, whereas Sustainability $(\mathcal{Q}_1)$, Resource Management $(\mathcal{Q}_2)$, and Product Lifespan $(\mathcal{Q}_3)$ belong to the effect or receiver group. These results highlight the interconnected nature of circular economy implementation: technological development and collaborative mechanisms can influence the broader system, while sustainability, resource management, and product lifespan reflect important outcomes of those interactions. The scatter representation complements the numerical analysis by making these dependencies easier to interpret and by showing which relationships exceed the adopted threshold.

From a managerial perspective, the results emphasize that circular economy development should not be approached through isolated criteria. Extending product lifespan, improving resource use, strengthening cooperation among stakeholders, and supporting technological innovation are mutually connected activities. A circular economy can contribute to sustainable development by reducing waste, encouraging resource recovery and reuse, extending the useful life of products, and supporting closed-loop production systems. The interval-valued formulation is particularly useful in this context because it allows decision-makers to work with imprecise expert information without forcing uncertain judgments into single deterministic values.

The study can be extended in several directions. Future research may compare the obtained causal structure with alternative MCDM and weighting techniques, including the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Criteria Importance Through Inter-criteria Correlation (CRITIC), and entropy-based procedures. Additional studies may also employ larger and more heterogeneous expert panels, alternative uncertainty representations, or different data sets to examine the stability of the identified relationships. From the model-development perspective, the circular economy criteria may be expanded to incorporate additional viewpoints related to business models, systems thinking, policy and regulatory alignment, and other application-specific factors. Such extensions would make it possible to test the robustness and transferability of the present findings in different circular economy contexts while preserving the causal interpretation offered by the DEMATEL framework.

Conflicts of Interest

The authors declare no conflicts of interest.

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