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Study on the Key Drivers to Improve the Circular Economy of Manufacturing Industry - An Application of Fuzzy Delphi Method & Grey Relational Analysis

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Keywords

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FDM
GRA

Abstract.

In order to implement Circular Economy (CE) smoothly, it is necessary to understand what kind of support the manufacturing industry needs on the road to CE, and to find out the technical indicators that can improve CE performance. This use the Multiple Attribute Decision Making (MADM) method to fill in the gaps in this research field. Through the distribution of questionnaires, experts are invited to provide data with reference to their professional experience. After data integration, the Fuzzy Delphi Method (FDM) method is used to screen out important driving factors and 9R indicators. Then, Grey Relational Analysis (GRA) is used to get important and key driving factors.
According to the FDM results of this study, the top 9R indicators are Reduce, Reuse, and Rethink. As for the GRA results, the top-ranking driving factors are the support of the parent company (headquarters), the promotion of the company's reputation and energy saving.

1. Introduction

1.1. Research background and motive

Taiwan is a densely populated island with limited natural resources. Decades of economic development resulted in massive consumption of resources (Chang et al., 2006). For those limited resources countries and remote islands, renewable and sustainable energy is clean energy from nature (Uyar & Beşikci, 2017). Economic growth of developing country lead to severe energy consumption after decades of development, which threatens human survival and development significantly, and this is the main reason for the deterioration of the environment (Bilgen, 2014).

Circular Economy (CE) has catch attention of the enterprises, society, and academia (Ferasso et al., 2020). The purposes of CE are to reduce the impact and damage of eco-

nomic development (Van Fan et al., 2019), to minimize the need for energy input and natural resources, to reduce waste, and maintain the resource value as long as possible. There is a certain relationship between the business cycle and the CE (Suchek et al., 2021), because they both involve economic development, including boom, recession, bust and recovery phases. These stages are usually caused by various economic factors, such as interest rate, government spending and investment, etc. (Hoffmann & Schnabl, 2011). The economic cycle has a great impact on people's lives, including: employment rate. According to the US Bureau of Labor Statistics, during the COVID-19 pandemic in 2021, the unemployment rate in the US also rose to 14.8% (Mejí a-Trejo et al., 2022). In practical applications, CE can play a role in various stages of the economic cycle (Primc et al., 2020). For example, during economic depression, CE can promote resource recovery and reuse, thereby reducing waste and reducing costs, while creating new job opportunities (Ghisellini et al., 2016), and promoting economic recovery. When the economy is prosperous, CE can reduce environmental pollution and waste of resources (Van Fan et al., 2019), and maintain the long-term sustainability of economic development. Therefore, there is an interaction and influence between CE and the business cycle (Suchek et al., 2021). The implementation of CE can achieve a better balance among environment, economy and society at the same time (Ghisellini et al., 2016; Geissdoerfer et al., 2017).

1.2. Research purpose

The manufacturing industry, which means uses mechanical appliances to produce components from raw materials. A booming manufacturing industry help to advance living standard. However, it also aggravates environmental problems, Bjørnbet et al. (2021) which make the producer pay more cost to maintain and remediate the environment. Therefore, these cost problems motivate the manufacturing industry to conduct a CE.

According to the literature review of CE, the introduction of CE concept will solve the following problems (Patwa et al., 2021): reduce the use of one-time use (Jun & Xiang, 2011), increase the proportion of renewable energy (Rokicki et al., 2020), reduce greenhouse gas and waste gas emissions (Liu et al., 2018), increase the reuse rate and recyclability of resources (Rossi et al., 2020). This study will focus on the manufacturing industry, discuss the importance of internal and external driving factors in the CE, understand what kind of assistance the manufacturing industry needs on the road to CE, and find out the 9R indicators that can improve CE performance.

Through the literature review of CE, it is found that there are not a few scholars who use the method of Multiple Attribute Decision Making (MADM) to conduct CE research. Therefore, this study chooses Fuzzy Delphi Method (FDM) to screen out the important driving factors and 9R indicators, and use Grey Relational Analysis (GRA) to find out the key driving factors. Understanding the importance of the driving factor, CE 9R indicators, and the performance evaluation of decision-making programs are the topics of this study. Through the review of this study, there are few cases where FDM combined with GRA method is applied to the key driving factors of CE and the key technologies of sustainable performance. Therefore, this study will fill this research gap.

2. Literature Review

2.1. Circular Economy (CE)

CE was first introduced by Boulding (1966) in ⟨⟨The Economics of the Coming Spaceship Earth⟩⟩. He declared: "The closed economy of the future might similarly be called the spaceman economy, in which the earth has become a single spaceship, without unlimited reservoirs of anything, either for the extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy." The concept of CE was first proposed by Pearce and Turner afterward. The purpose of CE is to build a sustainable resources management structure, make the economic system become part of the ecosystem, and establish the "condition of harmony in economy and environment" (Turner et al., 1993).

Mavi and Mavi (2019) has described the CE as "an economic model wherein resourcing, purchasing, production, and reprocessing are designed to consider environmental performance and human well-being". The main principle including redesign products, diverting the product and manufacturing process, increasing adaptability to cope with competition, managing waste effectively, and paying attention to renewable resources.

Anastasiades et al. (2020) pointed out the material flow of the CE, as illustrated in Figures 1 and 2. The former applies to most products' common circulatory system, and the latter applies to the circular system that uses natural resources, which is the perfect condition that a CE pursuit. It is to preserve the products and materials' recycled value or to manage non-reusable products in an environmentally friendly way in the final condemnation procedure.

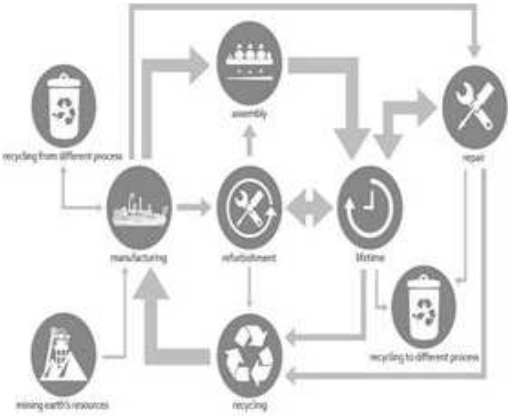

Figure 1: Material flows of CE (Anastasiades et al., 2020).

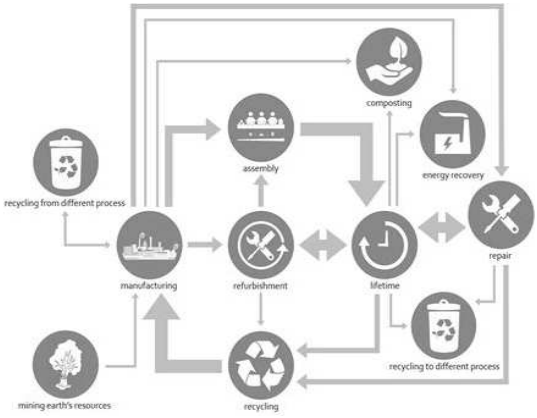

Figure 2: Use biological substances in the material flows of CE (Anastasiades et al., 2020)

2.2. Literature review of CE

For research on CE, if you search for the Chinese keywords CE and Driver, the number of related documents is extremely scarce. However, if you use the English keywords CE and Driver to conduct a Google Scholar search, you will find that this research topic is already in full swing. And the combination of MADM methods has been used in various CE studies, including the use of single and mixed multiple MCDM methods. For instance, Matinaro et al. (2019) used a single GRA method to find the key factors for the sustainable development of Taiwanese SMEs, Taghavi et al. (2021) used the Decision-making trial and evaluation laboratory (DEMATEL) method to find out the driving factors for the implementation of green supply chain management in the construction industry, such as Sharma et al. (2021) using Analytic Hierarchy Process (AHP) combined with DEMATEL to analyze the driving and obstacle factors for the implementation of Industry 4.0 sustainable supply chain management, Manoharan et al. (2022) using Interpretive Structural Modeling (ISM) combined with DEMATEL to analyze the key obstacles and driving factors in the implementation of CE in the automotive industry. Hartanto and Chang (2022) used the FDM and DEMATEL combined with the Analytic Network Process (ANP) to find out the resistance and facilitation factors faced by Taiwanese SMEs when implementing CE.

Table 1: Descriptions of Environmentally Friendly 9R.

References							
9R Principle	9R Principle code	9R Principle Factor	(1)	(2)	(3)	(4)	(5)
Reduce	R1	Reduce resources consumption	•	•	•	•	•
		Reduce waste		•	•	•	
Reuse	R2	Product reusability	•		•	•	•
		Resources sharing			•	•	
Recycle	R3	Recycle product			•	•	•
		Reuse the product or materials from waste		•	•	•	
Refuse	R4	Use renewable materials	•		•	•	
		Refuse to use dangerous or raw materials	•		•	•	•
Repair	R5	Repair product	•	•	•	•	•
Rethink	R6	Increase longevity of materials		•	•	•	
Refurbish	R7	Refurbish recycle products	•	•	•	•	•
Remanufacture	R8	Rebuild a recycled product to specifications of the original manufactured product	•		•	•	•
Repurpose	R9	Use prototype e.g. container as decoration	•	•	•	•	•

(1) Rossi et al., 2020; (2) Anastasiades et al., 2020; (3) Morseletto, 2020; (4) Reike et al., 2018; (5) Kirchherr et al., 2017.

2.3. Descriptions of environmentally friendly 9R

Kirchherr et al. (2017) pointed out that if an enterprise wants to gain a competitive advantage over its competitors and reach the state of Cleaner Production, it must

Table 2: Descriptions of Environmentally Friendly 9R.

Key Drivers/Code \ Scholars			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Internal	Strategy	(D1) Support of executives	•		•	•	•	•	•	•	
		(D2) Improve enterprise's reputation		•		•					
	Product	(D3) Remanufacture product			•				•		
		(D4) Increase longevity of product and service			•						
	Production	(D5) Technology renovation			•	•		•	•	•	
		(D6) Need for renewable resource			•			•			
		(D7) Cost reduction	•	•	•	•	•	•	•	•	
		(D8) Improve product quality	•	•			•				
	Resource	(D9) Energy conservation	•		•				•		
		(D10) Resource recovery of waste		•	•				•	•	
	Information	(D11) Share successful cases				•	•				
		(D12) Build information on CE	•	•		•	•		•		
	Government	(D13) Government legislation		•	•			•	•	•	
		(D14) Government support			•	•		•	•	•	
	Market	(D15) Obey the rules of the sales market		•							
		(D16) Satisfy consumer's needs				•		•	•		
External	Unit with relevant benefits	(D17) Support of parent company (Headquarters)	•						•	•	
		(D18) Pressure from stakeholders e.g. shareholders			•				•	•	
	Society	(D19) Improve competitiveness		•		•			•	•	
		(D20) CE's business pattern									
	Environment	(D21) Ecologic equilibrium	•		•			•			•
		(D22) Environmental justice								•	•

(1) Agyemang et al., 2019; (2) Zhang et al., 2021; (3) Lieder & Rashid, 2016; (4) Neri et al., 2018; (5) Sharma et al., 2021; (6) Patwa et al., 2021; (7) Hina et al., 2022; (8) Khan et al., 2022; (9) Stahel, 2010.

implement multiple R principles in production. Therefore, this study decided to use the 9R principles proposed by many scholars as a representative. As shown in Table 1, the study organized the descriptions of 9R.

2.4. Definition of key drivers and literature review

Key drivers were viewed as a measure or incentive for overcoming obstacles (Trianni et al., 2017). This study follows the Chapter 2 Literature Review and organizes scholars' points of view on key drivers. As shown in Table 2.

3. Methodology

This research uses a three-stage framework to find out the key driving factors and 9R indicators for the implementation of CE in the manufacturing industry. The structure of this study is shown in Figure 3. Firstly, the first stage is dedicated to literature review and industry expert suggestions, and puts forward the driving factors and 9R indicators of CE implementation. In the second stage, experts are required to use FDM to evaluate the importance of various driving factors and 9R indicators. In this stage, the important drivers are identified. In the third stage, the key drivers are obtained using the GRA, and the key drivers are ranked with the 9R indicators.

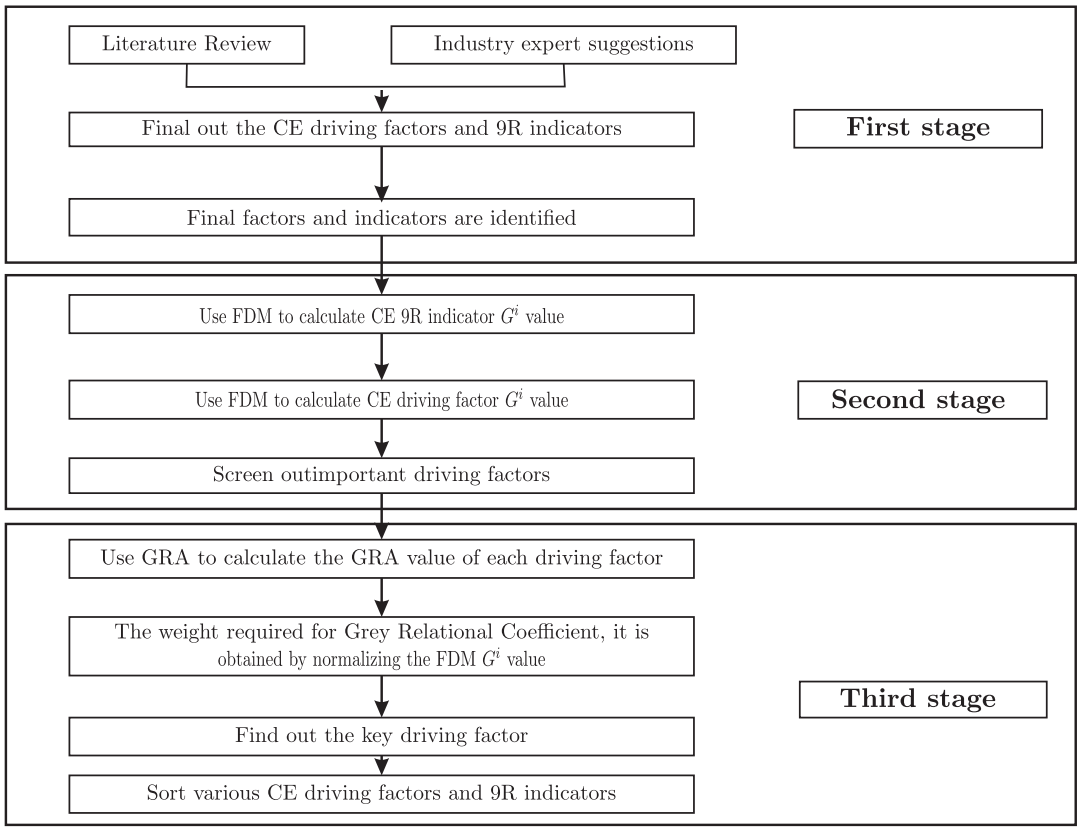

Figure 3: Structure of the study.

3.1. Fuzzy Delphi method

Murray et al. (1985) proposed the FDM by combining fuzzy set theory (Zadeh, 1965) with the Delphi method to address the fuzziness in experts' solutions to common problems. Kaufmann and Gupta (1988) applied the FDM for prediction processes. Ishikawa (1993) further developed a Delphi technique with triangular fuzzy numbers that overcomes deficiencies in the traditional Delphi method.

3.2. Fuzzy Delphi Method and its steps

Hsu et al. (2011) discussed the complete FDM proposed by Kaufmann and Gupta (1988), whose fussy set theory involves asking participants to provide a three-point estimate (pessimistic, moderate, and optimistic values) to form triangular fuzzy numbers. The importance of indicators is rated on a scale of 1−10 points.

Matched triangular fuzzy numbers fall into two types, namely conservative (C_L, C_M, C_U) and optimistic (O_L, O_M, O_U), with a set being compiled and consensus among the fuzzy expert opinions being generated. Finally, the conservative, moderate, and optimistic values are calculated to obtain the consensus value for each item (G^i). Compared with the traditional Delphi method, the FDM is more economically beneficial in terms of time and cost and can better reveal the opinions of a group of experts. The FDM is conducted using the following steps:

Step 1: For the confirmation of evaluation items, the researcher invites expert scholars and industry managers of related fields to construct an expert group and to give an interval of values to measure the degree of importance of the evaluation objectives. The "minimum value" of the interval represents the "most conservative cognitive value"; the "maximum value" represents the "most optimistic cognitive value."

Step 2: Collect questionnaire responses of the experts and calculate the most conservative (minimum) and optimistic (maximum) values of each item. Subsequently, calculate the minimum, geometric mean, and maximum of the remaining most conservative (C_L^i, C_M^i, and C_U^i, respectively) and most optimistic (O_L^i, O_M^i, and O_U^i, respectively) values for item perception ; the area marked with a h in the middle represents the gray area of fuzzy relations shown in Figure 4.

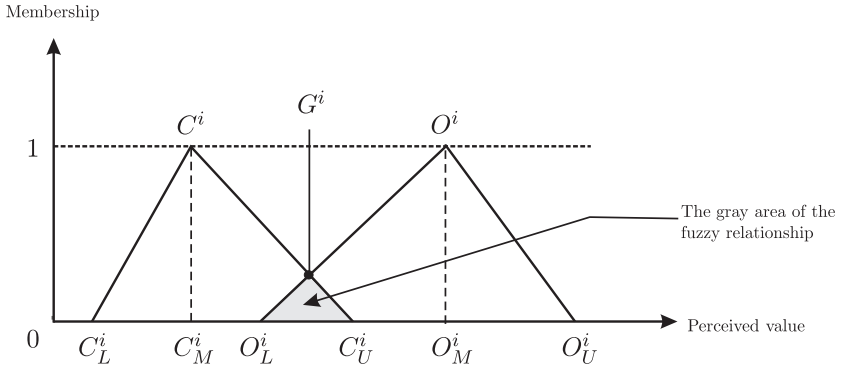

Figure 4: Grey area of fuzzy relations.

Step 3: Determine if agreement exists among the expert opinions and calculate the value of consensus significance G^i for each item. A large G^i value indicates a high level of consensus among experts for a particular item. The G^i calculation has three possible results.

The two triangular fuzzy numbers do not overlap, namely $C_U^i \leq O_L^i$. The result suggests that a consensus exists among the experts. The consensus importance value for item i, G^i, equals the mean values of C_M^i and O_M^i

$$G_i = \frac{C_M^i + O_M^i}{2}. \tag{3.1}$$

The two triangular fuzzy numbers overlap, with $C_U^i > O_L^i$ and $Z^i < M^i$, where $Z^i = C_U^i - O_L^i$ and $M^i = O_U^i - C_M^i$. The results reveal that the gray area of fuzzy relations is smaller than the interval between the geometric mean of optimistic perceived values and that of conservative perceived values. Although a consensus is not reached among the experts, their opinions are not divisive because the outlier opinions of experts do not differ substantially from those of other experts. In this case, the consensus importance value for item i is calculated using the equation proposed by Hsu et al. (2010) and Hsu et al. (2017) as follows:

$$G^i = [(C_U^i * O_M^i) - (O_L^i * C_M^i)]/[(C_U^i - C_M^i) - (O_M^i - O_L^i)]. \tag{3.2}$$

The two triangular fuzzy numbers overlap with C_U^i being $\geq O_L^i$; the gray area of the fuzzy relation (Z^i) is larger than the interval between the geometric mean of optimistic perceived values and that of conservative perceived values (M^i). Accordingly, the experts do not have consensus and are divided on their evaluation of a particular item because the opinions of experts with extremums differ considerably from those of others.

Step 4: Present items with no convergent opinions to the experts. Steps 1−5 are repeated for another questionnaire survey round until the opinions on all items have converged and consensus importance values (G^i) are obtained.

Step 5: Set a threshold value for G^i.

3.3. Reasons for choosing the grey relational analysis

Deng (1982) suggested that the GRA aims to solve MADM problems; it enjoys high calculation accuracy and is able to manage unclear information (Wu et al., 2002). If a questionnaire survey is to be designed based on the literature, the responses may lead to more than one first-priority factor (alternative), which increases the difficulty of decision-making. Accordingly, the GRA was employed to screen factors (alternatives) to avoid producing more than one first-priority factor (alternative) for decision makers.

3.4. GRA procedure

Step 1: Normalize the original decision-making matrix. In the GRA, data can be normalized under three principles: "the larger the better," "the nominal the best," or "the smaller the better." The relevant equations are presented as follows:

- If data for the decision-making indicator x_n are larger-the-better type:

$$x_{ij}^* = \frac{x_{ij} - \min\limits_i x_{ij}}{\max\limits_i x_{ij} - \min\limits_i x_{ij}}. \tag{3.3}$$

- If data for the decision-making indicator x_n are nominal-the-best type:

$$x_{ij}^* = \frac{|x_{ij} - x_{obj}|}{\max\limits_i x_{ij} - x_{obj}}. \tag{3.4}$$

- If the data for the decision-making indicator x_n are smaller-the-better type:

$$x_{ij}^* = \frac{\max\limits_i x_{ij} - x_{ij}}{\max\limits_i x_{ij} - \min\limits_i x_{ij}}. \tag{3.5}$$

Step 2. Convert data through normalization and calculate the GRA distance.

In the equation $\triangle_o ij = |x_{oj}^* - x_{ij}^*|$, $\triangle_{oij}$ denotes the difference between each normalized value and the normalized reference value.

Step 3. Calculate the grey relational coefficient.

A grey relational grade is the measurement equation for a grey relational space and is known as a local grey relational grade when only one sequence $x_0(k)$ is selected as the reference sequence. A grey relational coefficient must be obtained before the grey relational grade is calculated. In a grey relational space $\{P(x); \Gamma\}$ with a sequence ξ $(\xi(1), \xi(2), \ldots, \xi(k)) \in X$, where $i = 0, 1, 2, \ldots, m$ and $k = 1, 2, 3, \ldots, n \in N$, the grey relational coefficient corresponding to the local grey relational grade is calculated as follows:

$$\begin{aligned} \Gamma_{oij} &= \frac{\triangle \min + \xi \triangle \max}{\triangle_{oij} + \xi \triangle \max} \\ \triangle \max = \max_{i^*} \max_j \triangle_{oij}, &\quad \triangle \min = \min_{i^*} \min_j \triangle_{oij}, \quad \xi \in [0, 1]. \end{aligned} \tag{3.6}$$

Variable ξ in (4) is known as the distinguished coefficient and is used to control the value of a grey relational coefficient for distinction; ξ is typically set to the recommended value 0.5 (Deng, 1989) and can be adjusted by decision makers according to their preferences.

Step 4. Calculate the grey relational grade.

For each alternative, the grey relational coefficient is multiplied by a weight to obtain the weighted mean, which is the grey relational grade of the alternative. This grade is considered to be the alternative's score, with a high score indicating greater importance of a particular alternative. A grey relational grade is calculated using the following equation: Grey relational grade

$$\Gamma_{0i} = \sum_{j=1}^{n} (w_j \cdot \gamma_{0ij}). \tag{3.7}$$

Step 5. Determine the grey relational ordinal and select critical factors (alternatives) according to their grey relational grades. Decisions are made based on the grey relational grades (Γ_{0i}) obtained. An alternative with greater Γ_{0i} is considered more crucial; whereas an alternative with a smaller Γ_{0i} is less critical.

4. Data Validation and Analysis

This study identified 22 driving factors and 9R indicators that can help promote the implementation of CE. This research uses questionnaires to conduct data, collecting and distributing objects from Taiwan's manufacturing industry. A total of 15 enterprise experts were invited to form a team to fill out the questionnaire. All the applicants have been engaged in the relevant manufacturing industry for more than 10 years. The average value will be calculated after calculating the data in the 15 valid questionnaires recovered. Then, FDM and GRA methods are used to analyze the driving factors of this study and the degree of mutual influence of the environmentally friendly 9R on the CE performance of the manufacturing industry.

4.1 FDM Data Results

In this study, the driving factors in the questionnaire are coded with (Drivers, D) and environmentally friendly 9R is coded with (R). According to the FDM questionnaire, this study use the formula (3.1) (3.2) to calculate the G^i value of the driving factor and the 9R indicators, as shown in Table 4. Then, the experts were asked to set the G^i threshold value of the driving factor, set the threshold value of the driving factor as $G^i > 6.00$, and the important driving factors a total of 15 driving factors, as shown in Table 3.

Table 3: FDM analysis results of Environmentally Friendly R principles/ Drivers.

Environmentally Friendly R Principles	G^i	Ranking	Internal Drivers	G^i	External Drivers	G^i
R1	8.07	1	**D1**	**6.39**	**D12**	**6.23**
R2	7.49	2	**D2**	**6.10**	D13	5.65
R3	7.12	4	D3	5.95	**D14**	**6.08**
R4	6.15	9	**D4**	**6.07**	**D15**	**6.04**
R5	6.48	5	**D5**	**6.21**	**D16**	**6.12**
R6	7.22	3	D6	5.85	**D17**	**6.24**
R7	6.35	8	**D7**	**6.39**	**D18**	**6.27**
R8	6.38	7	D8	5.90	**D19**	**6.07**
R9	6.42	6	**D9**	**6.29**	D20	5.33
			D10	5.73	**D21**	**6.33**
			D11	**6.07**	D22	5.95

4.2. GRA data results

The study uses 15 drivers as the test items and 9 9R principles as performance indicators to analyze the interaction between drivers and environmentally friendly 9R of CE performance in the manufacturing industry. The calculation steps are as follows:

Step 1. Establish an original data evaluation matrix. Use data from 15 questionnaires to calculate the weighted average.

Step 2. Establish a normalized evaluation matrix. Use the larger the better principles and use equation (3.3) to establish a normalized evaluation matrix as shown in Table 4.

Table 4: Normalized Evaluation Matrix.

	R1	R2	R3	⋯	R7	R8	R9
D1	0.264	0.267	0.262	⋯	0.265	0.265	0.269
D2	0.268	0.263	0.262	⋯	0.257	0.270	0.249
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
D19	0.260	0.259	0.258	⋯	0.250	0.259	0.249
D21	0.245	0.244	0.242	⋯	0.242	0.247	0.253

Step 3. Convert data through normalization and calculate the GRA distance as shown in Table 5.

Table 5: GRA distance.

	R1	R2	R3	⋯	R7	R8	R9	MAX	MIN
D1	0.857	0.857	0.714	⋯	0.750	0.857	0.833	0.857	0.714
D2	1.000	0.714	0.714	⋯	0.500	1.000	0.000	1.000	0.000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
D19	0.714	0.571	0.571	⋯	0.250	0.571	0.000	0.714	0.000
D21	0.143	0.000	0.000	⋯	0.000	0.143	0.167	0.167	0.000
Max_i	1.000	1.000	1.000	⋯	1.000	1.000	1.000		
Min_i	0.000	0.000	0.000	⋯	0.000	0.000	0.000		

Step 4. Use equation (3.6) to calculate Grey Relational Coefficient as shown in Table 6.
Step 5. Use equation (3.7) to calculate Grey Relational Grade. For each alternative, the grey relational coefficient is multiplied by a weight to obtain the weighted mean, which is the grey relational grade of alternative as shown in Table 7. The weight is calculated according to the G^i value of FDM, after normalized calculationthen set the distinguished coefficient as 0.5 to calculate the Grey Relational Grade as shown in Table 8.

Table 6: Grey Relational Coefficient.

	R1	R2	R3	⋯	R7	R8	R9
D1	0.264	0.267	0.262	⋯	0.265	0.265	0.269
D2	0.268	0.263	0.262	⋯	0.257	0.270	0.249
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
D19	0.260	0.259	0.258	⋯	0.250	0.259	0.249
D21	0.245	0.244	0.242	⋯	0.242	0.247	0.253

Table 7: Grey Relational Grade.

R Index	R1	R2	R3	R4	R5	R6	R7	R8	R9
Weight	0.131	0.121	0.115	0.100	0.105	0.117	0.103	0.103	0.104

Table 8: Grey Relational Grade

	R1	R2	R3	⋯	R7	R8	R9	$\xi = 0.5$
D1	0.778	0.778	0.636	⋯	0.667	0.778	0.750	0.702
D2	1.000	0.636	0.636	⋯	0.500	1.000	0.333	0.757
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
D19	0.636	0.538	0.538	⋯	0.400	0.538	0.333	0.516
D21	0.368	0.333	0.333	⋯	0.333	0.368	0.375	0.354

Table 9: Ranking Table of Drivers.

	D1	**D2**	D4	D5	D7	**D9**	D11	D12	D14	D15	D16	**D17**	D18	D19	D21
$\xi = 0.5$	0.702	**0.757**	0.499	0.485	0.682	**0.734**	0.566	0.395	0.614	0.617	0.433	**0.847**	0.500	0.516	0.354
Rank	4	**2**	11	12	5	**3**	8	14	7	6	13	1	10	9	15

Step 6. Calculate the Grey Relational Grade, then ranked the Grey Relational Grade. Determine the Grey relational ordinal and select critical factors as shown in Table 9.

5. Conclusion

5.1. Research results

This study integrated 22 drivers and 9 R principles by collecting opinions from experts, using FDM and GRA to calculate the performance indicators. As the analysis stated above, this study proposes conclusions and suggestions below.

According to the FDM results of Table 3, after sorting, the results displayed that

the top 3 environmentally friendly R principles are: Reduce resources consumption (R1), Reduce waste (R2) of Reduce principle, and Reuse the product or materials from waste (R6) of Recycle principle, the description of the top 3 R principles are as following:

- Eliminate the production of waste instead of disposing of waste after it was produced. Make consumers buy products less frequently, use products longer. Reduction means using less natural resources, energy, raw materials, and produced waste. They can save materials and reduce costs by minimizing the conversion rate of waste materials and purchased materials (Morseletto, 2020).
- Morseletto (2020) indicated that recycling is processing materials to obtain higher quality and same quality materials. The current situation is that most of the materials enter the lower value cycle. The design of easy-to-recycle materials should be encouraged so that the materials can be used in the same industry or the same product to achieve the goal of permanent recycling, which means reducing the output of materials and wastes from the source, and processing. Recycling remains the most important strategy for countries around the world to face CE.

According to Table 9among the drives, the top 3 are Support of parent company (Headquarters) (D17) of Unit with relevant benefits, Improve enterprise's reputation (D2), and Energy Conservation (D9) of Strategy. These 3 drivers above are the key drivers for the implementation of CE. The following are descriptions of the top 3 drivers:

- They also want to receive support from the overseas parent company, such as manpower, funds, and machinery equipment. Moreover, some foreign literatures pointed out that it can help yield twice the result with half the effort when conducting CE (Agyemang et al., 2019; Khan et al., 2022).
- Companies are willing to implement sustainable related plans, one of the important factors is to be able to obtain a good corporate reputation (Costache et al., 2021), and through the implementation of CE, reputation and image can be effectively improved, which can effectively improve the relationship with consumers and can increase the market share of enterprises (Ormazabal et al., 2018).
- The full introduction of CE can save a lot of material costs every year (Agyemang et al., 2019). By economizing on the input of raw materials, can reduce the risks of chain scission and avoid the fluctuation in prices of raw materials (Su et al., 2013).

5.2. Research contribution

Compared with previous studies, there is no similar literature in Taiwan. This study is an innovative article. Although there are similar studies in foreign literature and also use single or multiple MADM methods. However, most of the methods used in this study have only been applied to supplier selection of supply chain management before, but there are few cases of application to key CE driving factors and key technologies of sustainable performance.

This study confirms that support from the parent company (headquarters), corporate reputation enhancement, energy conservation, support from senior management decision makers, and cost reduction are all key drivers of CE in the manufacturing industry. And among the 9R principles, 3R Reduce, Reuse, and Rethink can really improve the performance of CE technology in the manufacturing industry.

5.3. Research recommendations

This study is based on the method of MADM. The analysis results provide manufacturers with a road to CE as a reference for decision-making. For future research directions, this study proposes the following suggestions:

- If follow-up scholars want to conduct research on CE factors, they should use other MADM methods in the research method. However, in the process of filling out the questionnaire, experts will inevitably have inaccuracy and ambiguity in the rating of factors, so it is recommended can use Fuzzy Analytic Hierarchy Process (FAHP) to find out the weight value.
- In the future, Taiwan manufacturers will need to know not only the driving factors but also the barriers in promoting CE practice, so that they can get twice the result with half the effort in promoting CE. Therefore, it is suggested that follow-up scholars can study the barriers at the same time.

References

[1] Agyemang, M., Kusi-Sarpong, S., Khan, S. A., Mani, V., Rehman, S. T. & Kusi-Sarpong, H. (2019). Drivers and barriers to circular economy implementation: an explorative study in Pakistan's automobile industry, *Management Decision*, 57(4), 971-994. https://doi.org/10.1108/MD-11-2018-1178.

[2] Anastasiades, K., Blom, J., Buyle, M. & Audenaert, A. (2020). Translating the circular economy to bridge construction, Lessons learnt from a critical literature review, *Renewable and Sustainable Energy Reviews*, 117, 109522. https://doi.org/10.1016/j.rser.2019.109522.

[3] Boulding, K. E. (1966). The economics of the coming spaceship earth, New York, 1-17. https://doi.org/10.2307/1927631.

[4] Bilgen, S. (2014). Structure and environmental impact of global energy consumption, *Renewable and Sustainable Energy Reviews*, 38, 890-902. https://doi.org/10.1016/j.rser.2014.07.004.

[5] Bjørnbet, M. M., Skaar, C., Fet, A. M. & Schulte, K. Ø. (2021). Circular economy in manufacturing companies: A review of case study literature, *Journal of Cleaner Production*, 294, 126268. https://doi.org/10.1016/j.jclepro.2021.126268.

[6] Chang, K., Lee, T., & Chung, K. (2006). Solar water heaters in Taiwan, *Renewable Energy*, 31(9), 1299-1308. https://doi.org/10.1016/j.renene.2005.07.003.

[7] Costache, C., Dumitrascu, D. D. & Maniu, I. (2021). Facilitators of and barriers to sustainable development in small and Medium-sized enterprises: A descriptive exploratory study in Romania, *Sustainability*, 13(6), 3213. https://doi.org/10.3390/su13063213.

[8] Deng, J. (1982). Control problems of Grey Systems, *System and Control Letters*, 1(5), 288-294. https://doi.org/10.1016/S0167-6911(82)80025-X.

[9] Deng, J. (1989). Introduction to Grey System, *The Journal of Grey System*, 1(1), 1-24. https://doi.org/10.30016/JGS.200512.0003.

[10] Ferasso, M., Beliaeva, T., Kraus, S., Clauss, T. & RibeiroSoriano, D. (2020). Circular economy business models: The state of research and avenues ahead, *Business Strategy and the Environment*, 29(8), 3006-3024. https://doi.org/10.1002/bse.2554.

[11] Ghisellini, P., Cialani, C. & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, *Journal of Cleaner Production*, 114, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007.

[12] Geissdoerfer, M., Savaget, P., Bocken, N. M. & Hultink, E. J. (2017). The Circular Economy−A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048.

[13] Hsu, Y. L., Lee, C. H. & Kreng, V. B. (2010). The application of Fuzzy Delphi Method and Fuzzy AHP in lubricant regenerative technology selection, *Expert Systems with Applications*, 37(1), 419-425. https://doi.org/10.1016/j.eswa.2009.05.068.

[14] Hoffmann, A. & Schnabl, G. (2011). A vicious cycle of manias, crises and asymmetric policy responses−an overinvestment view, *The World Economy*, 34(3), 382-403. https://doi.org/10.1111/j.1467-9701.2011.01334.x.

[15] Hsu, C. W., Hu, A. H., Chiou, C. Y. & Chen, T. C. (2011). Using the FDM and ANP to construct a sustainability balanced scorecard for the semiconductor industry, *Expert Systems with Applications*, 38(10), 12891-12899. https://doi.org/10.1016/j.eswa.2011.04.082.

[16] Hsu, C. H., Chang, A. Y. & Luo, W. (2017). Identifying key performance factors for sustainability development of SMEs-integrating QFD and fuzzy MADM methods, *Journal of Cleaner Production*, 161, 629-645. https://doi.org/10.1016/j.jclepro.2017.05.063.

[17] Hartanto, M. R. & Chang, A. Y. (2022). Barrier and Driver Factor of Circular Economy in Small-Medium Enterprises Using Fuzzy Delphi Method and DANP Method [Paper presentation], 2022 *IEEE 4rd Eurasia Conference on IOT, Communication and Engineering* (ECICE), IEEE. October, 2022, Yunlin, Taiwan. https://doi.org/10.1109/ECICE47484.2019.8942669.

[18] Hina, M., Chauhan, C., Kaur, P., Kraus, S. & Dhir, A. (2022). Drivers and barriers of circular economy business models: Where we are now, and where we are heading, *Journal of Cleaner Production*, 333, 130049. https://doi.org/10.1016/j.jclepro.2021.130049.

[19] Ishikawa, T. (1993). Photoionization spectra of pd in high rydberg states, *Japanese Journal of Applied Physics*, 32(10R), 4779. https://doi.org/10.1143/JJAP.32.4779.

[20] Jun, H. & Xiang, H. (2011). Development of circular economy is a fundamental way to achieve agriculture sustainable development in China, *Energy Procedia*, 5, 1530-1534. https://doi.org/10.1016/j.egypro.2011.03.262.

[21] Kaufmann, A. & Gupta, M. M. (1988). *Fuzzy Mathematical Models in Engineering and Management Science*, Elsevier Science Inc. https://doi.org/10.1080/00401706.1990.10484661.

[22] Kirchherr, J., Reike, D. & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005.

[23] Khan, S. A., Mubarik, M. S. & Paul, S. K. (2022). Analyzing cause and effect relationships among drivers and barriers to circular economy implementation in the context of an emerging economy, *Journal of Cleaner Production*, 132618. https://doi.org/10.1016/j.jclepro.2022.132618.

[24] Lieder, M. & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry, *Journal of Cleaner Production*, 115, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042.

[25] Liu, Z., Adams, M., Cote, R. P., Chen, Q., Wu, R., Wen, Z. & Dong, L. (2018). How does circular economy respond to greenhouse gas emissions reduction: An analysis of Chinese plastic recycling industries, *Renewable and Sustainable Energy Reviews*, 91, 1162-1169. https://doi.org/10.1016/j.rser.2018.04.038.

[26] Murray, T. J., Pipino, L. L. & van Gigch, J. P. (1985). A pilot study of fuzzy set modification of Delphi, *Human Systems Management*, 5(1), 76-80. https://doi.org/10.3233/HSM-1985-5111.

[27] Matinaro, V., Liu, Y. & Poesche, J. (2019). Extracting key factors for sustainable development of enterprises: Case study of SMEs in Taiwan, *Journal of Cleaner Production*, 209, 1152-1169. https://doi.org/10.1016/j.jclepro.2018.10.280.

[28] Mavi, N. K. & Mavi, R. K. (2019). Energy and environmental efficiency of OECD countries in the context of the circular economy: Common weight analysis for malmquist productivity index, *Journal of Environmental Management*, 247, 651-661. https://doi.org/10.1016/j.jenvman.2019.06.069.

[29] Morseletto, P. (2020). Targets for a circular economy, *Resources, Conservation and Recycling*, 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553.

[30] Mejí a-Trejo, J., Sánchez Gutiérrez, J. & Patio-Karam, J. P. (2022). Key Fail Factors as Innovation Strategies To Be Avoided: A Comparative Study between Mexican and American Social Impact Startup in COVID-19 Pandemic Times, *Norteamérica*, 17(1), 217-264. https://doi.org/10.22201/cisan.24487228e.2022.1.512.

[31] Manoharan, S., Pulimi, V. S. K., Kabir, G. & Ali, S. M. (2022). Contextual relationships among drivers and barriers to circular economy: An integrated ISM and DEMATEL approach, *Sustainable Operations and Computers*, 3, 43-53. https://doi.org/10.1016/j.susoc.2021.09.003.

[32] Neri, A., Cagno, E., Di Sebastiano, G. & Trianni, A. (2018). Industrial sustainability: Modelling drivers and mechanisms with barriers, *Journal of Cleaner Production*, 194, 452-472. https://doi.org/10.1016/j.jclepro.2018.05.140.

[33] Ormazabal, M., Prieto-Sandoval, V., Puga-Leal, R. & Jaca, C. (2018). Circular economy in Spanish SMEs: challenges and opportunities, *Journal of Cleaner Production*, 185, 157-167. https://doi.org/10.1016/j.jclepro.2018.03.031.

[34] Primc, K., Kalar, B., Slabe-Erker, R., Dominko, M., & Ogorevc, M. (2020). Circular economy configuration indicators in organizational life cycle theory, *Ecological Indicators*, 116, 106532. https://doi.org/10.1016/j.ecolind.2020.106532.

[35] Patwa, N., Sivarajah, U., Seetharaman, A., Sarkar, S., Maiti, K. & Hingorani, K. (2021). Towards a circular economy: An emerging economies context, *Journal of Business Research*, 122, 725-735. https://doi.org/10.1016/j.jbusres.2020.05.015.

[36] Reike, D., Vermeulen, W. J. & Witjes, S. (2018). The circular economy: new or refurbished as CE 3.0? Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options, *Resources, Conservation and Recycling*, 135, 246-264. https://doi.org/10.1016/j.resconrec.2017.08.027.

[37] Rokicki, T., Perkowska, A., Klepacki, B., Szczepaniuk, H., Szczepaniuk, E. K., Bereziński, S. & Ziółkowska, P. (2020). The importance of higher education in the EU countries in achieving the objectives of the circular economy in the energy sector, *Energies*, 13(17), 4407. https://doi.org/10.3390/en13174407.

[38] Rossi, E., Bertassini, A. C., dos Santos Ferreira, C., do Amaral, W. A. N. & Ometto, A. R. (2020). Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases, *Journal of Cleaner Production*, 247, 119137. https://doi.org/10.1016/j.jclepro.2019.119137.

[39] Stahel, W. (2010). *The Performance Economy*, Springer. https://doi.org/10.1057/9780230274907_5.

[40] Su, B., Heshmati, A., Geng, Y. & Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation, *Journal of Cleaner Production*, 42, 215-227. https://doi.org/10.1016/j.jclepro.2012.11.020.

[41] Suchek, N., Fernandes, C. I., Kraus, S., Filser, M. & Sjögrén, H. (2021). Innovation and the circular economy: A systematic literature review, *Business Strategy and the Environment*, 30(8), 3686-3702. https://doi.org/10.1002/bse.2834.

[42] Sharma, M., Kamble, S., Mani, V., Sehrawat, R., Belhadi, A. & Sharma, V. (2021). Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies, *Journal of Cleaner Production*, 281, 125013. https://doi.org/10.1016/j.jclepro.2020.125013.

[43] Turner, R. K., Turner, R. K., Pearce, D. W. & Bateman, I. (1993). *Environmental Economics: An Elementary Introduction*, Johns Hopkins University Press. https://doi.org/10.1007/978-0-585-36577-0_12.

[44] Trianni, A., Cagno, E., Marchesani, F. & Spallina, G. (2017). Classification of drivers for industrial energy efficiency and their effect on the barriers affecting the investment decision-making process, *Energy Efficiency*, 10(1), 199-215. https://doi.org/10.1007/s12053-016-9455-6.

[45] Taghavi, E., Fallahpour, A., Wong, K. Y. & Hoseini, S. A. (2021). Identifying and prioritizing the effective factors in the implementation of green supply chain management in the construction industry, *Sustainable Operations and Computers*, 2, 97-106. https://doi.org/10.1016/j.susoc.2021.05.003.

[46] Uyar, T. S. & Beşikci, D. (2017). Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities, *International Journal of Hydrogen Energy*, 42(4), 2453-2456. https://doi.org/10.1016/j.ijhydene.2016.09.086.

[47] Van Fan, Y., Lee, C. T., Lim, J. S., Klemeš, J. J. & Le, P. T. K. (2019). Cross-disciplinary approaches towards smart, resilient and sustainable circular economy, *Journal of Cleaner Production*, 232, 1481-1491. https://doi.org/10.1016/j.jclepro.2019.05.266.

[48] Wu, H. H. (2002). A Comparative Study of Using Grey Relational Analysis in Multiple Attribute Decision Making Problems, *Quality Engineering*, 15(2), 209-217. https://doi.org/10.1081/QEN-120015853.

[49] Zadeh, L. A. (1965). Fuzzy sets, *Information and Control*, 8(3), 338-353. https://doi.org/10.1016/S0019-9958(65)90241-X.

[50] Zhang, A., Venkatesh, V. G., Wang, J. X., Mani, V., Wan, M., & Qu, T. (2021). Drivers of industry 4.0-enabled smart waste management in supply chain operations: a circular economy perspective in China, *Production Planning & Control*, 1-17. https://doi.org/10.1080/09537287.2021.1980909.

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