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CRITICAL SUCCESS FACTORS OF INDUSTRY 4.0 AND CIRCULAR ECONOMY TO ACHIEVE GREEN ECONOMY AND SUSTAINABLE DEVELOPMENT GOALS: A DEMATEL APPROACH

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Abstract

The COVID-19 pandemic, with its global reach, has presented businesses worldwide with unprecedented challenges, causing disruptions across various industries. Among these, the manufacturing sector faces significant issues related to unsustainable production and consumption patterns. In response to these challenges, the concepts of Industry 4.0 and the circular economy offer promising solutions by enabling advanced process control and sustainable resource management. This study is focused on identifying the critical success factors for implementing Industry 4.0 and circular economy practices within the Indian manufacturing industry. To achieve this, a quantitative analysis is conducted utilizing the DEMATEL approach. This analysis not only helps in selecting key factors but also aids in categorizing them into cause and effect groups. Three experts from the industry helped in exploring and data collection of the organization. The major findings are the identification of the ten major critical factors and their sub-factors. Out of this, the higest ranked factors are technological development, ethical and sustainable operations, and management support**.** The results of this research offer valuable insights for organizations looking to adopt Industry 4.0 and circular economy principles in their production environment, enabling them to progress towards a green economy and sustainable growth. Moreover, these findings can be of significance to both academic researchers and industry practitioners as they assess, implement, and benchmark Industry 4.0 technologies. The outcomes can inform the development of strategies focused on redesigning processes and promoting circularity within their respective domains.

Keywords: *Industry 4.0, Circular Economy, Sustainable Growth, DEMATEL.*

1. INTRODUCTION

In the present manufacturing industry, Industry 4.0 and circular economy are considered as key focal points. Additionally, in the global market the manufacturing industries are surviving because of a lack of resources and the lack of involvement of modern technology in the current production process. As a consequence, the rate of production decreases day by day, which leads to an unsustainable environment. To overcome such manufacturing issues, circular economy (CE) plays an critical role to manage available resources as well as reduction of unusual wastage using Industry 4.0 (I4.0) technologies to fulfil the industry's needs (Tseng et al., 2018; Rajput et al., 2019). Moreover, incorporating I4.0 into the circular economy framework will enable real-time data access, improve network monitoring, facilitate failure and error detection, ensure data transparency and reliability, and optimize resource circularity (Nascimento et al., 2019; Raj et al., 2020). In recent years, the concept of sustainable growth and green economy has gained significant attention as the global community recognizes the urgent need to address environmental challenges and achieve long-term prosperity. Sustainable growth refers to a development approach that takes into account not only economic considerations but also environmental and social factors. It emphasizes the efficient use of resources, the minimization of waste and pollution, and the promotion of social well-being. A key component of sustainable growth is the transition towards a green economy. A green economy aims to create a more sustainable and inclusive society by promoting environmentally friendly practices, renewable energy sources, and the efficient use of resources. It seeks to decouple economic growth from environmental degradation, ensuring that economic activities contribute to environmental conservation and social welfare. The shift towards a green economy requires a transformation across various sectors, including energy, transportation, agriculture, and manufacturing. It involves adopting cleaner technologies, implementing sustainable practices, and promoting circularity and resource efficiency. This transition not only mitigates environmental risks but also presents numerous economic opportunities, such as the development of green technologies, job creation, and enhanced competitiveness in global markets. The main purpose of this study is to recognize the existing obstacles that barrel manufacturing industries encounter when implementing CE and I4.0 practices. To achieve this, a multi-criteria decision-making method called Decision Making Trial and Evaluation Laboratory (DEMATEL) will be applied to prioritize the identified challenges. Furthermore, the study will recommend the most suitable decision-making approach for determining the critical success factors of CE and I4.0. The ABC barrel manufacturing industry will serve as an illustrative example for demonstrating the proposed methodology. Consequently, the study aims to address the following research question:

RQ1. What are the implementation challenges of I4.0 and CE?

RQ2. How to prioritise implementation challenges of I4.0 and CE?

2. RESEARCH BACKGROUND

The objective of I4.0 is to digitize and incorporate all physical resources into digital atmospheres throughout the entire value chain. It connects an embedded system of smart products into digital and physical processes. I4.0 based on real-time data transfer among different systems and sub-systems that increases digitalization in the entire supply chain. Six fundamental technologies of I4.0 were identified by Moktadir et al. (2018). These technologies encompass Cyber-Physical-Systems, the Internet of Things, Big Data, Cloud Computing, Cyber-Security, and Additive Manufacturing. On the other hand, the perception of the circular economy offers a sustainable solution by transitioning from a linear economic model to a circular model that promotes resource conservation and recycling (Martin et al., 2017). Product and service redesign and remanufacturing to eliminate unnecessary waste is central to the design out waste movement, as stated by the Ellen MacArthur Foundation in order (2017). Increased resource utilisation and biological performance at several points in the supply chain are two of CE's primary responsibilities (Nascimento et al., 2019).

2.1 Critical success factors of I4.0 and CE

The literature establishing the connection between I4.0 and CE which is still in the primary stage of development. Through a systematic literature review, the contemporary study identifies the critical success factors (CSF) on I4.0 and CE. Moreover, it is found that digital transformation and CE is way to move towards sustainable development (Ozkan-Ozen et al., 2020). Abdul-Hamid et al. (2020) identify the eighteen most significant challenges of I4.0 in CE context for the Palm-oil industry. According to him, lack of technology and virtulization is the essential challenge of the Palm oil industry. Furthermore, Ozkan-Ozen et al. (2020) suggested that lack of data analytics is the greatest significant challenge of I4.0 and CE in the initial stage. Aggarwal et al. (2019) explored DEMATEL approach and identified six major challenges of I4.0 and found that management commitment is the most prominent challenge for the Indian manufacturing industry. Further, Rajput et al. (2019) identified fifteen major challenging factors that connect I4.0 and CE, i.e. data analysis, smart device development, investment cost, infrastructure standardization, process digitalization etc. The critical success factors of I4.0 and CE are shown in Table 1. This study identifies ten key critical success factors and their criteria. The impact of these critical success factors and factors are explored in this table comprehensively.

Table 1: Critical success factors of I4.0 and CE

Code	Critical success factors	Sub-factors	References
CSF1	Technological development	Lack of standard data and technology transfer, lack of product technology improvement, lack of network facilities, lack of recycling technologies and lack of sensor technology.	**Beatriz et al. (2018); Moktadir et al. (2018); Kumar et al. (2020)**
CSF2	Complexity in integrating	Lack of awareness, lack of cooperation and compatibility, lack of data sharing protocol, and lack of information about modern technology.	**Walmsley et al. (2019); Tesch da Silva et al. (2020)**
CSF3	Data and cybersecurity	Information security, data governance, and privacy risks. System data and important industrial design or evidence must be protected from cybercrime like hacking.	**Tseng et al. (2018): Nascimento et al. (2019); Raj et al. (2020)**
CSF4	Big data and analytics	The challenges of combining different data sources are exacerbated by the complexity of data integration and the widely varying interpretations of the data elements.	**Rajput et al. (2019); Abdul-Hamid et al. (2020); Moktadir et al. (2018)**
CSF5	Deficiency of strategy	Lack of effective government assistance, poor leadership and management, high investment costs, unpredictability of return flows, and a lack of planning for implementing contemporary industries and the production environment.	**Schneider et al. (2018); Tseng et al. (2018); Sahu et al.(2023)**
CSF6	Employee fear and unemployment	The replacement of human labour with machines caused by the widespread implementation of contemporary technology in the manufacturing sector contributes to rising unemployment rates.	**De Sousa Jabbour et al. (2018); Kumar et al. (2020)**
CSF7	Collaborative model	Infrastructure gaps, lack of compatibility between man and machine and lack of vision.	**Tam et al. (2019); Walmsley et al. (2019)**
CSF8	Management support	Lack of funding of investors, lack of financial, economic feasibility, Insufficient backing from upper management, resistance from current employees, and a dearth of qualified candidates all contribute to a lack of progress.	**Martín et al. (2017); Luthra et al. (2018); Sahu et al. (2022)**

CSF9 **CSF10**	**Environmental effects** **Ethical and sustainable operations**	**Lack of environmental rules and regulations and large-scale automation has unintended consequences for the natural world, including substantial increases in energy use, depletion of regular resources, contamination, and the accumulation of electronic garbage. Traditional rules and regulations, lack of transparency and privacy, data ownership and security**	**Tseng et al. (2018); Nascimento et al. (2019); Bressanelli et al. (2019)** **Rajput et al. (2019); Aggarwal et al. (2019); Kumar et al. (2020)**

3. RESEARCH METHODS

The most important crucial success elements were determined and their interrelationships were developed using the DEMATEL technique. The authors developed a research path, as shown in Figure 1, to demonstrate the main processes taken for this investigation. This model explains all of the steps taken by the authors when investigating all of the critical success factors.

3.1 DEMATEL Approach

DEMATEL is an important MCDM approach that establishes causal and contextual relations (Gabus and Fontela, 1972). It has numerous benefits over AHP, ANP, TOPSIS and other MCDM approaches as it distributes critical success factors into cause and effect categories (Raj et al., 2020). The current study uses this technique to identify the most significant critical success factors affecting I4.0 and CE implementation and develop interrelationships among these critical success factors. The systematic DEMATEL approach is divided into the following steps. The following is a step-by-step methodology for implementing the DEMATEL approach is as follows:

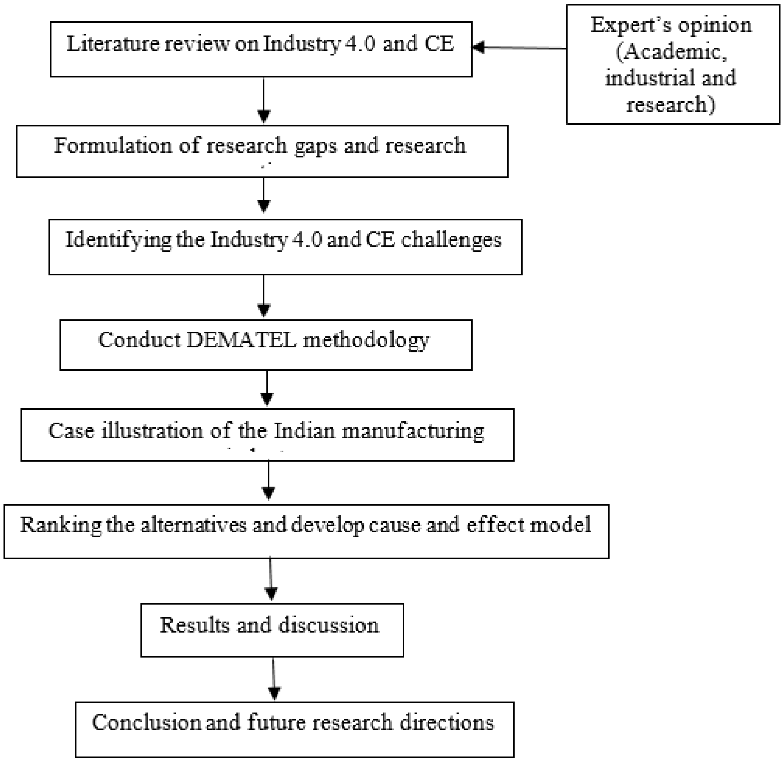

Fig. 1: Research path

Step 1**:** Construct the Average Direct Relation Matrix (A)

By examining the taken into consideration matrix, experts have expressed their opinions on how various difficulties interact with one another. An evaluation scale from 0 to 4 is used to gain expert opinions. "0 for no influence, 1 for low influence, 2 for medium influence, 3 for high influence, and 4 for very high influence" is how this scale's values are assigned. The DEMATEL scale is the name of this scale. Subsequently receiving the expert's advice, the typical direct-relation matrix—designated A—is produced. Table 2 displays the average direction-relation matrix's value.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \dots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \dots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \dots & a_{nn} \end{bmatrix}$$

Step 2**:** Evaluate the Normalized Matrix (B)

$$\lambda = \frac{1}{\mathrm{Max}_{1\le i\le n}\left(\sum_{j=1}^{n} a_{ij}\right)} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(1)}$$

Matrix B as presented in Table 3, is evaluated using Eq. (2), i.e. multiplying matrix B by a normalization factor (*λ)*.

$$B = A\mathrm{x}\,\lambda \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(2)}$$

Step 3: Finding the total relation matrix (C)

$$C = B\,(I - B)^{-1} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3)}$$

Eqn. (3) contributes to constructing the total relation matrix.

Where, I is the identity matrix.

Step 4: Computing the cause and effect values

In the scenario of a complete relationship matrix, we use Ei to represent the sum of values in the 'i'th row and Fj to represent the sum of values in the 'j'th row. From these sums, we derive two values: Ei+Fj, which signifies the connection between challenges, and Ei-Fj, which indicates the nature of the relationship in terms of cause and effect. Furthermore, positive values are used to classify challenges as causes, whereas negative values are used to classify them as effects.

4. Case illustration

For the case illustration of the suggested study, XYZ takes the barrel manufacturing business into account. As a result of India's largest MS Barrel producer, the normal industry is taken into account. With an overall 40% of the market share, ABC is the market leader in the barrel manufacturing sector. Moreover, when this product influences the end of its useful lifecycle, it produces a significant amount of waste. The industry-focused on lean culture, eliminating waste, and continual improvement. It has manufacturing, service, finance, and logistic units in the major cities in India. The industry has a major challenge of implement I4.0 and CE in their manufacturing unit. This work plays an essential contribution in the MS barrel manufacturing industry in obtaining an effective and efficient result for the continuous and recovery of barrel waste at a huge scale.

4.1 Application of DEMATEL Approach

The initial step in utilizing the DEMATEL approach involves generating the Average Direction-Relation Matrix (A), as depicted in Table 2. Subsequently, this matrix is normalized to ensure that all values fall within the 0 to 1 range, as per the formula outlined in Table 3 under Eq. (1). Following this normalization step, the total relation matrix (C) is generated, as shown in Table 4. Subsequent calculations are conducted following the methodology's steps, and the outcomes are reported in Tables 5 and 6. Table 5 displays the calculated values for 'Ei,' 'Fj,' 'Ei + Fj,' and 'Ei - Fj,' which assist in problem analysis. The 'Ei - Fj' values are used to categorize the challenges into two groups: 'Cause' and 'Effect,' as presented in Table 6.

Table 2: Average (direction relation) Matrix

	CSF1	**CSF2**	**CSF3**	**CSF4**	**CSF5**	**CSF6**	**CSF7**	**CSF8**	**CSF9**	**CSF10**
CSF1	0	3	3.33	3	2	2.67	2.67	2.33	3.33	2.33
CSF2	2.33	0	1.67	1.33	2.67	1.33	3.67	3.33	1.67	2.33
CSF3	3.33	2	0	3.67	1.33	1	2.67	3	1	2
CSF4	2.33	1	2.67	0	1	1	1.67	1.33	1	1.67
CSF5	1	3.67	1.33	1.33	0	2.33	1.33	2.33	1.67	2.33
CSF6	3	1.33	1	1.67	2.33	0	1.33	1.67	1	2.67
CSF7	3.33	2.33	1.33	1	2.67	1.67	0	2.67	1	2.33
CSF8	2.33	2.67	1	1.33	3.33	2.33	3.67	0	1.33	3
CSF9	3.33	1	1.33	1	1.67	1	3	2.33	0	3.67
CSF10	3.33	2.33	3.67	2.33	2.67	1.67	2.67	2	3.67	0

Table 3: Normalize Matrix

	CSF1	**CSF2**	**CSF3**	**CSF4**	**CSF5**	**CSF6**	**CSF7**	**CSF8**	**CSF9**	**CSF10**
CSF1	0	0.1217	0.135	0.1217	0.0811	0.1083	0.1083	0.0945	0.135	0.0945
CSF2	0.0945	0	0.0677	0.0539	0.1083	0.0539	0.1488	0.135	0.0677	0.0945
CSF3	0.135	0.0811	0	0.1488	0.0539	0.0406	0.1083	0.1217	0.0406	0.0811
CSF4	0.0945	0.0406	0.1083	0	0.0406	0.0406	0.0677	0.0539	0.0406	0.0677
CSF5	0.0406	0.1488	0.0539	0.0539	0	0.0945	0.0539	0.0945	0.0677	0.0945
CSF6	0.1217	0.0539	0.0406	0.0677	0.0945	0	0.0539	0.0677	0.0406	0.1083
CSF7	0.135	0.0945	0.0539	0.0406	0.1083	0.0677	0	0.1083	0.0406	0.0945
CSF8	0.0945	0.1083	0.0406	0.0539	0.135	0.0945	0.1488	0	0.0539	0.1217
CSF9	0.135	0.0406	0.0539	0.0406	0.0677	0.0406	0.1217	0.0945	0	0.1488
CSF10	0.135	0.0945	0.1488	0.0945	0.1083	0.0677	0.1083	0.0811	0.1488	0

Table 4: Total Relation Matrix (C)

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	Di
CSF1	0.4765	0.5034	0.4764	0.4482	0.4719	0.4080	0.5508	0.5064	0.4473	0.5251	4.8141
CSF2	0.4900	0.3452	0.3655	0.3369	0.4438	0.3219	0.5203	0.4806	0.3446	0.4616	4.1103
CSF3	0.5149	0.4071	0.3015	0.4175	0.3835	0.3016	0.4762	0.4579	0.3142	0.4373	4.0117
CSF4	0.3692	0.2761	0.3136	0.2061	0.2742	0.2247	0.3318	0.3007	0.2354	0.3213	2.8531
CSF5	0.3853	0.4232	0.3088	0.2944	0.2948	0.3145	0.3844	0.3939	0.3030	0.4072	3.5096
CSF6	0.4336	0.3286	0.2896	0.2978	0.3615	0.2182	0.3609	0.3504	0.2715	0.3989	3.3110
CSF7	0.4902	0.4057	0.3330	0.3060	0.4159	0.3141	0.3570	0.4293	0.3029	0.4313	3.7854
CSF8	0.4989	0.4517	0.3511	0.3430	0.4747	0.3635	0.5261	0.3680	0.3414	0.4928	4.2113
CSF9	0.5012	0.3618	0.3414	0.3110	0.3849	0.2927	0.4723	0.4211	0.2704	0.4833	3.8400
CSF10	0.5964	0.4842	0.4905	0.4277	0.4941	0.3752	0.5517	0.4968	0.4627	0.4396	4.8190
Rj	4.7563	3.9871	3.5715	3.3885	3.9993	3.1346	4.5316	4.2051	3.2932	4.3983	

5. RESULT AND DISCUSSION

Under DEMATEL approach, based on detailed discussions with industrial, academic and research experts and analyzing the existing literature related to manufacturing decision-making. The result table 5 demonstrations the raking values for the challenges. Ei+Fj denotes the degree or magnitude of the relationship with other challenges. The Ei+Fj value of technological development challenge (Ch1) is 9.5704, followed by ethical and sustainable operations challenge (Ch10) with a value of 9.2174, which are higher than other implementation challenges. Therefore, it is considered the most important challenge of the considered industry. Additionally, if the value of Ei-Fj is greater than zero, then it will be considered as a cause category, i.e. (Ch9) environmental effects challenge. If the value of Ei-Fj is less than zero, then it will be considered as an effect category, i.e. (Ch7), i.e. collaborative model.

Table 5: The Degree of Influence Given and Received on Challenges

Challenges	Ei	Fj	Ei-Fj	Ei+Fj	Ranking
CSF1	4.8141	4.7563	0.0578	9.5704	1
CSF2	4.1103	3.9871	0.1232	8.0974	5
CSF3	4.0117	3.5715	0.4402	7.5832	6
CSF4	2.8531	3.3885	-0.5354	6.2417	10
CSF5	3.5096	3.9993	-0.4896	7.5089	7
CSF6	3.3110	3.1346	0.1764	6.4455	9
CSF7	3.7854	4.5316	-0.7462	8.3171	4
CSF8	4.2113	4.2051	0.0063	8.4164	3
CSF9	3.8400	3.2932	0.5468	7.1332	8
CSF10	4.8190	4.3983	0.4207	9.2174	2

Table 6: Ranking the Challenges in Cause and Effect categories

Cause		Effect	
Challenges	Ranking	Challenges	Ranking
CSF9	1	CSF7	1
CSF3	2	CSF4	2
CSF10	3	CSF5	3
CSF6	4		
CSF2	5		
CSF1	6		
CSF8	7		

6. CONCLUSION

In the present context, the implementation of I4.0 and CE practices is still in its early stages. This research employs the principles of I4.0 and CE to conduct an empirical case study within the Indian MS barrel manufacturing industry. Given the effect of the COVID-19 pandemic, there is a growing necessity for manufacturing sectors to embrace digital transformation and resource circularity to meet evolving customer demands.

This study addresses two key research questions. To respond to the first research question (RQ1), we identified and analyzed ten significant challenges, underscoring the significance of technological advancement, ethical and sustainable operations, as well as managerial support in the successful implementation of I4.0 and CE within the manufacturing domain. The second research question

(RQ2) is tackled by employing the DEMATEL approach to prioritize these challenges. It's important to note that this study has a limitation in that it exclusively focuses on the challenges related to the implementation of I4.0 and CE. Future research endeavors could explore other integration factors and additional I4.0 technologies such as risk management and product redesign.

Additionally, while the present analysis concentrates on the barrel manufacturing industry, future analyses will encompass other manufacturing sectors such as tire recycling, food and beverage, and more.

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