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A decision support model to enhance reconfigurable manufacturing system performance through integration of Industry 4.0 and circular economy practices

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Abstract

The COVID-19 pandemic, volatile market conditions, shorter lifecycles, and cost-effective goods confront the reconfigurable manufacturing system (RMS). The RMS needs Industry 4.0 and circular economy technologies to boost performance. However, present literature does not integrate these technology and methods. This paper proposes a framework for adopting these technologies and practices. The SWARA method determines relative weights of specified practices, Pythagorean fuzzy COCOSO ranks performance indicators based on expert opinion, along with sensitivity analysis. The important performance metrics in key criteria practices are production lead time, advanced technology usage, and machine utilization rate, according to the report. Waste reduction and production costs are also important to experts. Managers can use the framework to increase RMS performance and handle COVID-19. It enables practitioners use sophisticated technology and CE practices and evaluate their success using metrics.

Keywords: *Reconfigurable manufacturing system, SWARA, COCOSO, performance evaluation, Industry 4.0, Circular economy*

1. Introduction

Reconfigurable manufacturing systems (RMS) can meet customized customer requirements by combining advanced technologies with techniques such as agile manufacturing, just in time, and others. As a result, RMS is best suited for dynamic market conditions, as it can modify production functionality as well as capacity to satisfy dynamic market needs [34]. Also, according to [19], pandemics has

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severely impacted the supply chain resulting in the lower production efficiencies. RMS key characteristics ("Modularity, Integrability, Customization, Scalability, Diagnosability, and Convertibility") facilitate high responsiveness in the system. The main components that provide flexibility is "reconfigurable machine tools (RMTs)", "reconfigurable assembly machines (RAMs)", "reconfigurable inspection machines (RIMs)", and "reconfigurable fixtures". RMS can reconfigure its hardware (such as machine settings, layout configuration, etc.) and software programming to provide market-adjustable technology [32]. Furthermore, the Covid-19 pandemic has created many difficulties for the manufacturing industry, such as volatile product demand, production constraints, manpower shortages, employee recruitment and retention, changing customer expectations, and disrupted supply chains [19, 25]. In addition, the challenges of changing technologies and the requirements of sustainable manufacturing are becoming increasingly important. Another issue that manufacturing industries are dealing with as a result of Covid-19 is data security in the workplace. Hence, over the last two years, manufacturing industries have struggled to reduce the demand-supply gap. This has disrupted the economic performance of most manufacturing systems. Manufacturing systems must be extremely adaptable and able of producing goods that are inexpensive [18, 27]. Researchers believe that implementing Industry 4.0 technologies are necessary to meet the market's changing requirements and thus improve the industries' economic performance. AI, IoT, BDA, VR, AR, Blockchain, Supply chain techniques, autonomous robots, and other key Industry 4.0 technologies may be included [45]. Furthermore, the circular economy (CE), which has three primary beliefs: keep goods in use, design out waste, and revitalize natural systems, can help to reduce manufacturing costs and thus improve manufacturing system performance. Furthermore, the digitization in Industry 4.0 can result in survivable CE, demonstrating a strong link between CE and Industry 4.0 [3, 26]. In addition, [35] carried out systematic literature review (SLR) for links of CE and Industry 4.0; they also proposed a framework for it. In this way, Industry 4.0 and CE can help improve RMS performance and, as a result, repurpose manufacturing systems to alleviate the effects of Covid-19 pandemic. This was unexplored in the current literature; hence, the current research aims to investigate it and construct a framework to enhance RMS performance through "Industry 4.0 technologies" and "Circular economy practices".

Researchers [18] added that use of "Industry 4.0 technologies" can result in the optimization of manufacturing activities, so future RMS must be aligned with these technologies. Simultaneously, the efficient and effective use of resources provided by CE practices can result in the ecological and economic growth in organization. Therefore, combining "Industry 4.0 technologies", "Circular economy practices", and "RMS performance metrics" was required for enhancing adoption and its RMS performance. Several RMS researchers investigated the advantages of advanced technologies on RMS performance that can incorporate smart capabilities [1, 18]. Additionally, some RMS researchers attempted to implement CE practices to improve RMS performance [1]. In contrast, the current literature was fairly limited in the area of the link between of "Industry 4.0 technologies", "Circular economy practices", and "RMS performance metrics". Consequently, there was a significant need to research the benefits of the nexus effect on RMS performance and create a framework for their implementation. This can help to increase RMS adoption and CE practice adoption in the manufacturing industry, resulting in more sustainable manufacturing. The purpose of this research is to identify "Industry 4.0 technologies", "Circular economy practices", and "RMS performance metrics", determines their weights, and prioritizes RMS performance metrics.

Therefore, the study objectives are listed below:

- Conduct a literature review to list “Industry 4.0 technologies”, “Circular economy practices”, and “RMS performance metrics” including supply chain techniques.
- Evaluate the influence of “Industry 4.0 technologies” and “Circular economy practices” on RMS performance.
- Prioritize RMS performance metrics based on “Industry 4.0 technologies”, “Circular economy practices”, and “RMS performance metrics”.

Several previous research have reported enablers, practices, and performance metrics for RMS [30]. Similar studies were conducted for Industry 4.0 as well as CE, with advanced technologies in Industry 4.0 and prominent practices in CE being mentioned. However, the existing articles do not reflect an integrated view of RMS, Industry 4.0, and CE. Existing research did not integrate prominent practices for RMS, Industry 4.0, and CE. Furthermore, the present articles do not address the impact of industry adoption of these practices on RMS performance and environmental metrics. Hence, the current study conducts a literature study to list “Industry 4.0 technologies”, “Circular economy practices”, and “RMS performance metrics”. “Stepwise Weight Assessment Ratio Analysis (SWARA)” method and “Pythagorean fuzzy combined compromise solution (COCOSO)” method were applied to evaluate weights of practices and rank performance metrics respectively. The present research aims to address research gaps in RMS adoption and integrate it with CE practices to improve performance. It also focuses on ranking RMS performance metrics to evaluate the efficacy of integrating CE and RMS practices. The research suggests that such frameworks can improve RMS performance and customer satisfaction, potentially leading to increased adoption. This research advances theoretical knowledge and demonstrates the use of SWARA and Pythagorean fuzzy COCOSO techniques. The study at hand consists of six sections, including the present section. Section 2 contains a literature review of RMS, CE, Industry 4.0, and research gaps, and Section 3 discusses research methodology. Section 4 describes the case analysis, including framework development along with performance metric ranking, and Section 5 describes the findings of the research and implications. The study’s conclusion and future scope are summarized in Section 6.

2. Literature review

Initially, Scopus database was utilized to discover for articles on “Reconfigurable Manufacturing Systems (RMS)”, “Circular economy”, and “Industry 4.0”. Here, 1140 research papers were found, with 281 chosen for the study, excluding English and peer-reviewed articles.

2.1. Reconfigurable manufacturing system and manufacturing industries

Volatile customer demands and emerging markets around the world are driving up RMS demand in manufacturing industries. RMS can also assist with the repurposing of disrupted supply chains, manufacturing operations, and unprecedented increases in demand for some products (e.g. Medical related products) as a result of pandemic [18, 27]. As a result, the RMS is attracting the attention of many researchers and practitioners, with nearly 60% of research articles published on RMS from 2010 to 2017 [43]. Manufacturing automation in RMS, according to [18], incorporates agility, reduced costs, and increased throughputs in the system with the help of modern systems like “cyber-physical systems (CPS)”, “digital twins”, etc. Due to these advantages of RMS adoption in the era of Industry 4.0 and to meet post-pandemic needs, it is gaining popularity among manufacturing industries. According to [12], implementing sustainability along with RMS results in several benefits such as increased responsiveness, lower costs, reduced waste, lower power consumption, improved safety, health, and environmental benefits. The latest technologies, as well as CE practices, help RMS performance improvement in a variety of ways, as discussed in this section.

2.2. Industry 4.0 and CE practices

“Industry 4.0 technologies” can help in sustainable development while also leveraging CE. These technologies have the potential to optimize resource consumption while also assisting in decision and policymaking [7]. At the moment, it is vital to look into the advantages of cutting-edge technologies and CE practices during RMS adoption, as well as enhancements in performance. Hence, current study focuses on effectiveness of “Industry 4.0 technologies” and “Circular economy practices” on RMS performance, referred to as the I4.0-CE nexus effect. To accomplish this, an examination of the pertinent research was carried out to list the key “Industry 4.0 technologies” and “Circular economy practices” which are described below.

The authors in [18] have completed review of RMS articles to find the Industry 4.0 and RMS enabling technologies. They focused on several advanced technologies, like CPS, Digital twins, additive manufacturing, DMS, IoT, cloud manufacturing, AR/VR, etc., and mentioned that collaboration of these technologies can be beneficial for RMS adoption. The researchers defined CPS as computational integration systems, whereas IoT refers to systems in which machines/parts are connected by the internet. They further defined cloud computing as services with most reliability, availability, and scalability. [7] also attempted to find the combined effect that “Industry 4.0 technologies” and “Circular economy practices” in attaining the SDGs. They studied the correlation ship between practices such as automation and robotics, global standard adoption, cybersecurity, and others. Additionally, [16] carried out review of RMS layout design articles wherein they considered advanced technologies such as additive manufacturing, material handling systems, optimization of layout design and infrastructure, etc. According to the researchers, the optimization approaches can solve the majority of the RMS layout problems. [3] proposed a model which could link Industry 4.0 practices with sustainable production and CE. Several CE practices were investigated in this study, including “10R approaches”, “waste analysis”, “artificial intelligence (AI)” and “machine learning (ML)”, “big data analytics (BDA)”, “quality 4.0”, etc. Furthermore, [40] proposed a framework to address “sustainable supply chain management” issues, taking into account a variety of issues such as safety improvements, supply chain collaboration, employee education and training, customer feedback, and satisfaction, etc. The researchers computed the relative importance of practices using “best-worst method (BWM)” and identified solution measures for them. Many other researchers, such as [5], emphasized the Ergonomic design of RMS as an important technology in RMS, whereas [13] recognised remote monitoring and sensors as an important technology in RMS. The extensive literature review resulted in a list of 29 practises, as shown in Table 1.

Table 1. Industry 4.0 and CE practices

Sr. No.	Industry 4.0-CE practice	Description	Reference
1	Adoption of technologies like CPS, Digital twins	Adoption of advanced technologies can help with automation and improve RMS reconfigurability	[18]
2	Implementation of automation and Robotics	In a manufacturing plant, robotics can increase flexibility and decrease lead time.	[7]
3	Availability of additive manufacturing facilities	Availability of additive manufacturing facilities can speed up product development and shorten lead times	[16]
4	Adoption of distributed manufacturing system (DMS)	Advanced technologies, such as DMS, provide better control over production activities, resulting in increased productivity	[18]
5	Installation of advanced material handling systems	The availability of modern and programmable material handling systems may assist in minimizing the time needed to switch to another product	[14, 16]
6	Implementation of remote monitoring and sensors	Remote monitoring and sensors assist in maintaining better control over production activities. They can also improve product quality.	[13, 28]
7	Execution of 10R approaches	The approaches can save resources and, as a result, the product's manufacturing cost.	[3, 33]
8	Adoption of global standards and SDG	This can increase the product's acceptance around the world and, as a result, sales	[17]
9	Use of eco-friendly packaging materials	This can lead to less environmental degradation as well as recognition from authorities	[9]

Sr. No.	Industry 4.0-CE practice	Description	Reference
10	Execution of waste analysis	Waste analysis can help to reduce manufacturing waste and, as a result, manufacturing costs.	[3]
11	Availability of safety improvement initiatives	Safety precautions can help to reduce accidents and, as a result, damage to people and property.	[39]
12	Appointment of sustainability experts	The sustainability expert can effectively implement all CE practices, resulting in maximum benefits.	[9]
13	Optimization of layout and infrastructure	Better resource utilization, such as layout and infrastructure, can result in lower manufacturing costs and investment savings.	[16]
14	Implementation of 4M practices	The 4M practices can help discover the underlying causes of specific manufacturing effects.	[38]
15	Effective energy utilization and consumption	This can assist to decrease energy costs and the environmental impact of energy consumption.	[9]
16	Ergonomical design practices	The ergonomic design of a workspace can result in a better workplace for workers and, as a result, higher productivity.	[5]
17	Availability of optimization techniques	The availability of optimization tools and techniques can help to improve implementation and, as a result, cost savings.	[8, 44]
18	Eco-design for material synthesis	Eco-design can help to mitigate the harmful effects of hazardous materials.	[6]

Sr. No.	Industry 4.0-CE practice	Description	Reference
19	Adoption of IoT and Cloud techniques	The advanced features assist automation and, as a result, RMS reconfigurability.	[18, 22]
20	Adoption of cybersecurity in manufacturing	This can help to prevent the theft of sensitive manufacturing data, allowing the organization to stay competitive.	[7]
21	Synchronization of AI & ML approaches	Advanced data processing technologies such as AI and ML can assist in product development and reduce lead time.	[3, 4]
22	Penetration of big data analytics in existing systems	Technologies such as BDA assist in the analysis of data generated during product design and manufacturing, which helps in decision making.	[3]
23	Adoption of VR/AR in-process structure	AR/VR helps in product development simulations, which can reduce lead time.	[18]
24	Use of system integration and simulation techniques	These techniques can formulate the input-output relationship and describe complex interactions.	[36]
25	Supply chain collaboration	Manufacturing delays can be reduced through collaboration with suppliers.	[40]
26	Employee education/training	Employees who are multi-skilled as a result of education and training help in production activities, improve product quality, and reduce delays.	[39, 41]
27	Adoption of Quality 4.0	Quality improvement practices can lead to increased customer satisfaction and, as a result, improved performance.	[3, 23]

Sr. No.	Industry 4.0-CE practice	Description	Reference
28	Monitoring of customer feedback and satisfaction	This is related to taking continuous customer feedback and hence improving product quality for customer satisfaction.	[21, 39]
29	Adoption of R & D activities	R&D activities are critical for new product development and performance enhancement.	[2]

2.3. RMS performance metrics

When implementing the chosen practices, it is essential to evaluate their impact on RMS using a number of performance metrics. As a result, performance measures were identified through an analysis of literature to reflect the nexus effects of "Industry 4.0 technologies" and "Circular economy practices" on RMS, as detailed below. [29] has carried a SLR and meta-analysis of RMS research articles to identify enablers, barriers, and RMS performance metrics. To evaluate RMS performance, the researchers identified a variety of metrics such as machine utilization rate, production lead time, guarantee/warranty claims, percentage defectives, etc. [16] identified parameters such as the use of advanced technologies while reviewing RMS articles related to layout design, whereas [7] considered parameters such as waste reduction, renewable energy usage, etc. when evaluating the nexus effect of "Industry 4.0 technologies" and "Circular economy practices". Furthermore, [39] proposed a framework for the adoption of lean manufacturing wherein they used parameters such as energy consumption rate, accident reduction rate, customer complaint rate, profit percentage, etc. to evaluate manufacturing companies. Furthermore, [7] investigated the nexus that exists between Industry 4.0 and CE practices in terms of waste reduction, renewable energy usage, and other metrics that can reflect the influence of practices on manufacturing organization performance. In their literature review on sustainable production and CE, researchers [3] considered parameters such as product recycle rate. These researchers' contributions resulted in the set of 17 performance measures identified using an article review, as depicted in Table 2.

Table 2. Performance measures of RMS

Sr. No.	Performance metrics of RMS	Description	Reference
1	Advanced technology usage	It represents the number of the latest 'Industry 4.0' technologies implemented in RMS.	[16]
2	Machine utilization rate	It highlights percentage of time for which machine or system is used.	[30]

Sr. No.	Performance metrics of RMS	Description	Reference
3	Production lead time	It is the time required to complete product manufacturing activities.	[29]
4	Waste reduction	It denotes a reduction in waste over a specific period.	[7]
5	Energy consumption rate	It represents the total amount of electricity and fuel used during manufacturing activities.	[39]
6	Renewable energy usage	It focuses on use of energy produced using renewable sources.	[7]
7	Accident reduction rate	It refers to reduction in workplace accidents as the consequence of the implementation of safe practices.	[39]
8	Manpower utilization rate	It is the fraction of available manpower time utilized on production activities.	[38]
9	Manufacturing cost reduction	It indicates a decrease in product manufacturing costs as a result of chosen practices.	[37]
10	Soft practices adopted	It denotes number of software technologies that have been adopted for manufacturing-related activities.	[20]
11	Customer complaint rate	It represents the number of customer complaints about the product supplied.	[39]
12	Scrap rate	It indicates a decrease in scrap due to the nexus impact caused by selected practices.	[20]
13	Profit percentage	It indicates the increase in profit due to adoption of selected practices.	[28, 39]

Sr. No.	Performance metrics of RMS	Description	Reference
14	Number of guaranty/warranty claims	It represents the number of customer claims for product guarantee/warranty. It also indicates the quality of the manufactured product.	
15	Manufacturing flexibility	It indicates a variety of products that can be produced using system.	[18]
16	Product recycle rate	It represents number of products which are recycled for reducing harmful environmental effects.	[3, 24]
17	Percentage defectives	The percentage of defective products detected during quality checks out of total products manufactured is referred to as the percentage of defectives.	[31]

The implementation of the aforementioned practices expects the improvement in specified performance metrics, as well as the RMS's performance. The performance measures identified can help to evaluate the impact of specific "Industry 4.0 technology" as well as "Circular economy practices". This may assist to understand the research status of RMS as well as the effectiveness of specific practices.

2.4. Literature gaps

A comprehensive analysis of selected research papers revealed advanced technologies, CE practices, and metrics. In addition to these practices, this domain has the following research gaps.

- The existing RMS articles do not contain an exhaustive list of modern "Industry 4.0 technologies" that can help enhance RMS performance.
- Only a few researchers had focused on CE practices which may improve RMS performance.
- The nexus impact of "Industry 4.0 technologies" including "Circular economy practices" on RMS performance was not explored in current literature.
- It is required to evaluate the weights of identified practices to reflect their relative significance and impact on RMS performance.
- There is no evidence in the existing literature for a collection of performance metrics which may capture impact of "Industry 4.0 technologies" and "Circular economy practices" on RMS performance.

- Prioritizing RMS performance metrics using practices' weights is required to determine the relative impact of selected practices.
- It is critical to have a framework in place that may help in the adoption of "Industry 4.0 technologies" and "Circular economy practices" across manufacturing companies, as well as to measure RMS performance. Expert opinion and the application of appropriate "multi-criterion decision-making (MCDM)" tools may help with this.

This study establishes a framework for ranking RMS performance metrics by reviewing the literature for "Industry 4.0 technologies" and "Circular economy practices". Also, the study focuses on the interplay between these technologies and CE practices on RMS performance, demonstrating their potential for significant improvement.

3. Research methodology

To address the aforementioned gaps, a literature review looks into "Industry 4.0 technologies", "Circular economy practices", and "RMS performance metrics". The Scopus search engine was accessed for RMS-related research articles with the keyword "Reconfigurable Manufacturing System". Several filters were then applied to the articles, yielding a final list of 281 peer-reviewed articles published in English by Springer, Elsevier, Taylor & Francis, Emerald, and others. These articles are then thoroughly analysed to determine RMS practices. Additional CE articles were retrieved and reviewed in order to identify CE practices. Figure 1 depicts the overall direction of the presented research.

This research aims to study "Industry 4.0 technologies" and "Circular economy practices" on RMS performance and identifies performance metrics. An expert panel is formed to gather feedback on framework development. The SWARA method categorizes and weights practices, and the Pythagorean fuzzy COCOSO technique ranks performance metrics. Sensitivity analysis evaluates a framework's robustness under various conditions. The expert panel then evaluates the findings' applicability.

4. Case analysis

The expert panel selected for the study and the steps of developing a framework are discussed below.

4.1. Industry identification and data collection

Authors wanted to incorporate industry professionals' expertise into the framework, so they approached 26 companies, five of which accepted to help develop it. The five companies (C1, C2, ….. C5) all based in Mumbai, India, manufacture household products such as plastic bottles and sanitizer dispensers. Each company employs 100 to 125 employees, including technical officers, and has similar production capacities, with a turnover of approximately 60 to 70 crore Indian rupees. In terms of design and production volume, all of the selected companies faced the same challenge: changing customer demands. As a result, 15 experienced and qualified professionals have been included in the panel for the framework development process. Some of the professionals selected work in the RMS domain, while others work on CE initiatives. Also, some of the professionals explored the adoption and utilization of advanced production equipment. Table 3 contains a detailed description of these professionals.

Table 3. Details of experts

Code	Age (Years)	Highest qualification	Role in industry	Department	experience (Years)
E1(C1)	41-50	Post graduate	Founder/Director	Sustainability	16
E2(C1)	31-40	Graduate	Manager	Design	18
E3(C2)	41-50	Post graduate	Vice president	Circular economy	26
E4(C2)	41-50	Ph. D.	Senior Manager	Manufacturing	21
E5(C5)	31-40	Post graduate	Logistics Manager	Design	18
E6(C2)	41-50	Graduate	Sales Manager	Manufacturing	25
E7(C1)	60+	Ph. D.	CE consultant	Circular economy	36
E8(C3)	21-30	Graduate	Junior Engineer	Design	05
E9(C3)	51-60	Ph. D.	Production manager	Manufacturing	32
E10(C3)	41-50	Post graduate	Vice president	Design	21
E11(C4)	51-60	Post graduate	Director	R&D	33
E12(C4)	41-50	Graduate	Production Manager	Manufacturing	23
E13(C4)	51-60	Ph. D.	General Manager	R&D	34
E14(C5)	51-60	Post graduate	Sustainability expert	Design	33
E15(C5)	41-50	Ph. D.	Production Manager	Administration	22

Following the formation of the expert panel, a number of meetings took place, both individually and collectively, to explain the entire process and solicit feedback. Following the collection of responses, calculations were performed, and the results were shown to the panel at the most recent meeting, where the possible consequences of the obtained results were discussed.

4.2. Framework development

The expert panel was then presented with all study information, including selected practices and performance metrics. The experts were then asked to divide the chosen practices into five major groups, as illustrated in Figure 2.

4.3. Multi-method analysis

MCDM methods are computational and mathematical tools which may assist in decision making. The weights of practices were calculated employing SWARA technique, while RMS performance metrics were prioritized using "Pythagorean fuzzy COCOSO" technique. These methods are described further below, and the analysis results are also presented here.

4.3.1. Application of the SWARA method

This technique was established by researcher [11]. During their research, several researchers utilized weight calculating approaches like "analytic hierarchy process (AHP)", "fuzzy AHP", "best-worst method (BWM)", "weighted sum method (WSM)", "SWARA", and others. Each of these methods has benefits and drawbacks. The SWARA technique was chosen for this study because it is suitable for scenarios in which criterion weights are mostly generated from expert knowledge and practical experience. Unlike methods like AHP, which involve numerous pairwise comparisons and consistency checks, SWARA allows experts to evaluate the relative importance of criteria using a simple sequential evaluation process. This considerably reduces experts' cognitive stress, particularly when dealing with many criteria, as in the current study. The relative importance of practices was calculated using unique SWARA technique, which ranks alternatives according to their significance, starting from maximum weight and proceed to the smallest in importance. In addition, the SWARA approach computes the criteria significance efficiently and evaluates expert opinion. The SWARA method analysis requires the following steps [31].

- Arrange the alternatives in a decreasing sequence of importance. For this, experts are requested to compare the criteria using a scale of 0 to 1.
- Calculate the Kj value using the equation,

$$K_j = \begin{cases} 1 & j = 1 \\ S_j + 1 & j > 1 \end{cases}$$

• Evaluate the relative importance of practices employing,

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{(J-1)}}{K_j} & j > 1 \end{cases}$$

• Obtain weights as given below,

$$W_j = \frac{q_j}{\sum_{j=1}^{N} q_j}$$

The panel was now requested to suggest a comparison, and the weights of each alternative were computed using the SWARA processes outlined above. Table 4 shows the sample comparison and weights.

Table 4. Sample of weight computation table

Sr. No	Major criteria weights	Average value (S_j)	$K_j = (1 + S_j)$	$q_j = (q_{j-1})/K_j$	$W_j = q_j/\sum(q_j)$
1	TOP	0.0000	1.0000	1.0000	0.3685
2	SOP	0.6000	1.6000	0.6250	0.2303
3	EOP	0.3500	1.3500	0.4630	0.1706
4	ASP	0.2500	1.2500	0.3704	0.1365
5	QOP	0.4500	1.4500	0.2554	0.0941

The average weights were calculated using the aforementioned calculations for major criteria and sub-criteria practices from assessments produced by all 15 panel experts, as well as all sub-criteria. Global weights were subsequently obtained by taking product of major criteria weights with sub-criteria weights, and the outcomes are depicted using Table 5.

Table 5. Obtained global weights

Major criteria	Major criteria weights	Sub-criteria	Sub-criteria weights	Global weights
TOP	0.2292	TOP1	0.2006	0.0460
		TOP2	0.1982	0.0454
		TOP3	0.1500	0.0344
		TOP4	0.1311	0.0300
		TOP5	0.1834	0.0420
		TOP6	0.1367	0.0313
SOP	0.1857	SOP1	0.2017	0.0375
		SOP2	0.1858	0.0345
		SOP3	0.1753	0.0326
		SOP4	0.1424	0.0265
		SOP5	0.1479	0.0275
		SOP6	0.1469	0.0273
EOP	0.1717	EOP1	0.1997	0.0343
		EOP2	0.1995	0.0343
		EOP3	0.1212	0.0208
		EOP4	0.1790	0.0307
		EOP5	0.1505	0.0258
		EOP6	0.1501	0.0258
ASP	0.2284	ASP1	0.2062	0.0471
		ASP2	0.1510	0.0345
		ASP3	0.1875	0.0428
		ASP4	0.1419	0.0324
		ASP5	0.1410	0.0322
		ASP6	0.1724	0.0394
QOP	0.1849	QOP1	0.1616	0.0299
		QOP2	0.2221	0.0411
		QOP3	0.2301	0.0426
		QOP4	0.1721	0.0318
		QOP5	0.2141	0.0396

The global weights obtained highlight the relative relevance of selected practices, implying that the factors with highest weights should be prioritized and targeted first.

4.3.2. Pythagorean fuzzy COCOSO method

The COCOSO method offers a consistent weight variation solution, ensuring stability in decision-making processes. It combines a “simple additive method (SAM)” and an exponentially “weighted product method (WPM)” to achieve a compromise solution. Researchers used a Pythagorean fuzzy set to deal with uncertainty problems. This method is effective in separating suitable alternatives and avoiding counterintuitive phenomena [27]. The “intuitionistic fuzzy sets”, “hesitant fuzzy sets” and “Pythagorean fuzzy sets” can all manage ambiguous and error problems; also, “intuitionistic fuzzy sets” handle imprecision better, while “hesitant fuzzy sets” composed of discrete values within [0, 1] in lieu a particular value. Furthermore, "Pythagorean fuzzy sets" provide added freedom to decision-makers when placing values when sum of both membership and non-membership scores is higher than one and total of squares falls between zero and one. The steps involved when using the Pythagorean fuzzy COCOSO technique are shown below [10, 42].

• Start with initial decision matrix using a linguistic scale as depicted in Table 6

Table 6. Scales used in ‘Pythagorean fuzzy COCOSO’ method

Term used	Fuzzy number (μ)	Fuzzy number (ν)
Extremely low (EL)	0	1
Very low (VL)	0.1	0.9
Low (L)	0.2	0.8
Middle low (ML)	0.3	0.7
Below middle (BM)	0.4	0.6
Middle (M)	0.5	0.5
Above middle (AM)	0.6	0.4
Middle high (MH)	0.7	0.3
High (H)	0.8	0.2
Very high (VH)	0.9	0.1
Extremely high (EH)	1	0

During a brainstorming session with all the experts, the first pairwise comparison matrix was developed. While the majority of the experts were present virtually, some were physically present during the brainstorming session. As a result, all the experts agreed upon a single pairwise comparison matrix at the end.

• Develop a Pythagorean fuzzy decision matrix, with rows representing performance metrics and columns representing practices or criteria.

$$r'_{ij} = \begin{cases} \frac{r_{ij}-r_j^-}{r_j^+-r_j^-}, & \text{if } j \in B, \\ \frac{r_j^+-r_{ij}}{r_j^+-r_j^-}, & \text{if } j \in C \end{cases}$$

Where, $r_j^- = \min r_{ij}$ and $r_j^+ = \max r_{ij}$

• Prepare weighted comparability sequence employing the formula,

$$S_i = \sum_{j=1}^{n} w_j * r'_{ij}$$

• Compute the Pi using,

$$P_i = \sum_{j=1}^{n} (r'_{ij})^{w_j}$$

• Evaluate weight using the following equations,

$$K_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m} (P_i + S_i)}$$

$$K_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i}$$

$$K_{ic} = \frac{\lambda S_i + (1-\lambda) P_i}{\lambda \max_i S_i + (1-\lambda) \max_i P_i} \quad 0 \leq \lambda \leq 1$$

The λ parameter for the COCOSO method was set to 0.5. This value represents an equal balance between the COCOSO model's aggregation components, ensuring that all alternatives are evaluated without bias toward additive or multiplicative compromise measures.

• Calculate assessment value using equation and then prepare ranking based on it.

$$K_i = \sqrt[3]{K_{ia} K_{ib} K_{ic}} + \frac{K_{ia} + K_{ib} + K_{ic}}{3}$$

Initially, the comparison matrix was developed using input from experts, as shown in Table 7 and Table 8.

Table 7. Linguistic decision matrix (Part 1)

Code	TOP1	TOP2	TOP3	TOP4	TOP5	TOP6	SOP1	SOP2	SOP3	SOP4	SOP5	SOP6	EOP1	EOP2
Weight	0.0460	0.0454	0.0344	0.0300	0.0420	0.0313	0.0375	0.0345	0.0326	0.0265	0.0275	0.0273	0.0343	0.0343
PM1	VH	VH	MH	H	AM	AM	AM	H	AM	AM	AM	AM	AM	AM
PM2	H	VH	H	MH	H	H	H	MH	AM	AM	MH	MH	MH	ML
PM3	EH	EH	VH	H	VH	H	H	H	ML	H	H	MH	H	ML
PM4	H	H	MH	VH	H	M	H	VH	M	M	M	H	MH	VH
PM5	M	MH	L	ML	MH	L	L	M	BM	BM	M	BM	M	BM
PM6	ML	ML	ML	ML	L	L	H	ML	ML	ML	ML	AM	L	ML
PM7	MH	M	L	H	M	M	H	M	L	L	L	M	H	H
PM8	H	MH	M	H	M	L	MH	ML	L	L	M	L	AM	M
PM9	H	M	VH	H	MH	H	M	H	M	H	MH	H	H	M
PM10	MH	AM	MH	L	M	MH	L	M	ML	M	MH	MH	M	M
PM11	AM	M	MH	M	AM	M	MH	M	M	M	AM	M	AM	MH
PM12	H	AM	M	H	M	MH	M	H	M	M	M	H	M	M
PM13	VH	MH	H	H	MH	MH	MH	L	M	H	L	H	M	ML
PM14	M	AM	M	M	AM	L	AM	ML	M	AM	AM	MH	L	VH
PM15	M	MH	L	H	M	L	VH	M	M	M	M	MH	ML	M
PM16	BM	M	BM	M	ML	BM	M	H	L	H	VH	H	L	H
PM17	H	MH	M	MH	AM	H	MH	H	ML	ML	AM	M	AM	M

Table 8. Linguistic decision matrix (Part 2)

Code	EOP3	EOP4	EOP5	EOP6	ASP1	ASP2	ASP3	ASP4	ASP5	ASP6	QOP1	QOP2	QOP3	QOP4
Weight	0.0208	0.0307	0.0258	0.0258	0.0471	0.0345	0.0428	0.0324	0.0322	0.0394	0.0299	0.0411	0.0426	0.0318
PM1	H	H	AM	AM	H	H	VH	VH	VH	VH	VH	H	VH	VH
PM2	H	H	AM	AM	AM	AM	VH	VH	VH	H	H	H	H	H
PM3	VH	H	H	H	H	MH	VH	H	H	H	H	H	MH	MH
PM4	MH	M	H	MH	H	H	M	MH	H	M	M	H	M	L
PM5	L	L	M	BM	M	L	ML	AM	L	AM	ML	M	AM	BM
PM6	L	ML	AM	AM	AM	AM	L	L	L	L	L	H	L	L
PM7	L	H	L	MH	M	H	L	M	H	MH	M	L	L	M
PM8	VH	L	H	L	H	MH	H	H	H	MH	L	H	MH	L
PM9	MH	MH	H	MH	H	M	MH	MH	MH	H	MH	MH	MH	H
PM10	AM	M	M	AM	M	M	MH	AM	MH	M	AM	M	AM	M
PM11	M	L	MH	M	MH	L	MH	M	H	MH	MH	AM	H	H
PM12	H	ML	MH	M	H	M	M	H	M	M	H	M	AM	H
PM13	AM	MH	MH	MH	H	M	H	H	H	MH	MH	MH	MH	MH
PM14	M	M	L	M	M	M	AM	M	AM	M	AM	ML	AM	M
PM15	H	AM	ML	M	AM	MH	ML	H	L	AM	M	H	M	M
PM16	H	M	BM	H	M	H	BM	L	AM	AM	AM	AM	BM	L
PM17	MH	M	MH	AM	M	MH	AM	AM	M	M	AM	M	AM	AM

The above procedure was then followed, and the ranking is shown in Table 9.

Table 9. Ranking of RMS performance metrics

Code	Kia	Kib	Kic	Ki	Rank obtained
PM1	0.0696	5.7652	0.9985	3.0152	2
PM2	0.0671	5.3972	0.9616	2.8455	3
PM3	0.0676	5.9117	0.9696	3.0455	1
PM4	0.0665	5.0239	0.9539	2.6979	5
PM5	0.0479	2.4772	0.6862	1.5038	16
PM6	0.0344	2.0000	0.4938	1.1668	17
PM7	0.0447	3.0867	0.6407	1.7028	15
PM8	0.0497	3.7718	0.7126	2.0226	12
PM9	0.0690	5.2613	0.9894	2.8175	4
PM10	0.0604	3.5698	0.8660	2.0703	11
PM11	0.0634	4.2281	0.9088	2.3580	8
PM12	0.0655	4.2608	0.9391	2.3951	7
PM13	0.0596	4.5945	0.8549	2.4528	6
PM14	0.0554	3.1872	0.7949	1.8657	14
PM15	0.0604	3.8160	0.8661	2.1654	10
PM16	0.0556	3.4009	0.7964	1.9495	13
PM17	0.0630	3.9285	0.9036	2.2388	9

4.3.3. Sensitivity analysis

Along with prioritizing performance metrics, the proposed framework must be evaluated to test its robustness. Hence, to test the framework's robustness, a sensitivity analysis was carried out, outcomes of which are depicted in Table 10 and Table 11.

Table 10. Sensitivity analysis of obtained ranking

Short Code	Performance metrics	EXPT. 1 0%	EXPT. 2 2%	EXPT. 3 5%	EXPT. 4 8%	EXPT. 5 10%	EXPT. 6 15%	EXPT. 7 20%	EXPT. 8 25%
PM1	Advanced technology usage	3.0152	3.0157	3.0166	3.0174	3.0180	3.0194	3.0208	3.0222
PM2	Machine utilization rate	2.8455	2.8459	2.8467	2.8474	2.8479	2.8491	2.8503	2.8515
PM3	Production lead time	3.0455	3.0461	3.0472	3.0482	3.0489	3.0506	3.0523	3.0541
PM4	Waste reduction	2.6979	2.6982	2.6986	2.6990	2.6993	2.7000	2.7007	2.7014
PM5	Energy consumption rate	1.5038	1.5032	1.5024	1.5016	1.5010	1.4997	1.4983	1.4970
PM6	Renewable energy usage	1.1668	1.1665	1.1660	1.1656	1.1653	1.1645	1.1638	1.1630
PM7	Accident reduction rate	1.7028	1.7028	1.7029	1.7029	1.7029	1.7030	1.7030	1.7031
PM8	Manpower utilization rate	2.0226	2.0227	2.0229	2.0230	2.0232	2.0235	2.0238	2.0241
PM9	Mfg. cost reduction	2.8175	2.8178	2.8183	2.8188	2.8191	2.8199	2.8207	2.8216
PM10	Soft practices adopted	2.0703	2.0701	2.0697	2.0694	2.0691	2.0685	2.0680	2.0674
PM11	Customer complaint rate	2.3580	2.3580	2.3580	2.3579	2.3579	2.3579	2.3579	2.3579
PM12	Scrap rate	2.3951	2.3950	2.3948	2.3947	2.3946	2.3943	2.3941	2.3938
PM13	Profit percentage	2.4528	2.4531	2.4536	2.4541	2.4545	2.4553	2.4562	2.4570
PM14	Guaranty/warranty claims	1.8657	1.8654	1.8649	1.8644	1.8640	1.8632	1.8623	1.8615
PM15	Manufacturing flexibility	2.1654	2.1651	2.1647	2.1643	2.1641	2.1635	2.1628	2.1622
PM16	Product recycle rate	1.9495	1.9492	1.9487	1.9483	1.9479	1.9472	1.9464	1.9456
PM17	Percentage defectives	2.2388	2.2386	2.2384	2.2382	2.2381	2.2378	2.2374	2.2371

As discussed, sensitivity analysis should carry out to assess the robustness of research outcomes obtained in current research. The sensitivity analysis finds variations among final solutions obtained by the hybrid SWARA and Pythagorean fuzzy COCOSO approach for performance metric prioritization. When the weights of practices are changed, the variations must be examined. The robustness is tested by running 17 experiments with varying practice weights. The weight of each individual practice is fixed to the maximum value while the weights of other practices are fixed to equal values, according to the observations made from 17 experiments. The same thing can be seen from the first to the last experiment. Figure 3 shows that 17 experiments were conducted during sensitivity analysis, with the variations obtained in the results of performance metrics ranking being negligible, indicating robustness of proposed framework. The variations obtained are less than 10% and thus acceptable. This demonstrates the framework's applicability and how it can be used in a variety of situations.

5. Discussion

The study enhances previous research on RMS adoption and performance improvement by developing theories, integrating "Industry 4.0 technologies" and "Circular economy practices", and "RMS practices".

Table 11. Sensitivity analysis of obtained ranking

Short Code	Performance metrics	EXPT. 9 -2%	EXPT. 10 -5%	EXPT. 11 -8%	EXPT. 12 -10%	EXPT. 13 -15%	EXPT. 14 -20%	EXPT. 15 -25%	Rank obtained
PM1	Advanced technology usage	3.0146	3.0138	3.0129	3.0124	3.0109	3.0095	3.0081	2
PM2	Machine utilization rate	2.8450	2.8442	2.8435	2.8430	2.8418	2.8406	2.8394	3
PM3	Production lead time	3.0448	3.0437	3.0427	3.0420	3.0403	3.0386	3.0369	1
PM4	Waste reduction	2.6977	2.6972	2.6968	2.6965	2.6958	2.6951	2.6945	5
PM5	Energy consumption rate	1.5043	1.5051	1.5059	1.5065	1.5079	1.5092	1.5106	16
PM6	Renewable energy usage	1.1671	1.1675	1.1680	1.1683	1.1691	1.1698	1.1706	17
PM7	Accident reduction rate	1.7028	1.7028	1.7027	1.7027	1.7027	1.7026	1.7026	15
PM8	Manpower utilization rate	2.0224	2.0223	2.0221	2.0220	2.0217	2.0214	2.0211	12
PM9	Mfg. cost reduction	2.8171	2.8166	2.8161	2.8158	2.8150	2.8142	2.8133	4
PM10	Soft practices adopted	2.0705	2.0709	2.0712	2.0715	2.0721	2.0727	2.0733	11
PM11	Customer complaint rate	2.3580	2.3580	2.3580	2.3580	2.3580	2.3581	2.3581	8
PM12	Scrap rate	2.3952	2.3953	2.3955	2.3956	2.3958	2.3961	2.3963	7
PM13	Profit percentage	2.4524	2.4519	2.4514	2.4511	2.4502	2.4494	2.4485	6
PM14	Guaranty/warranty claims	1.8660	1.8666	1.8671	1.8674	1.8683	1.8691	1.8700	14
PM15	Manufacturing flexibility	2.1656	2.1660	2.1664	2.1667	2.1673	2.1680	2.1686	10
PM16	Product recycle rate	1.9498	1.9503	1.9508	1.9511	1.9519	1.9527	1.9535	13
PM17	Percentage defectives	2.2389	2.2391	2.2393	2.2395	2.2398	2.2402	2.2405	9

5.1. Study findings

Initially, the SWARA method was used to determine each practice's influence on RMS adoption and performance i.e. weights. The results of this weight computation of major group criteria show that technology-oriented practices are the highest priority for this. [18, 30] had a similar discussion, which supports the current study's findings. As stated by [7], modern "Industry 4.0 technologies" can significantly transform design, production operations, and transportation, so the expert panel assigned the most weight to TOP. As discussed by [30]; [32], expert panel ranked advanced soft practices second, indicating their significance in the production sector. According to [7], soft technologies like cloud computing and AR are technological pillars of manufacturing organizations, so ASP came in second place in the analysis. This is followed by sustainable manufacturing practices, which have the capability to decrease both production costs and negative environmental effects. To sustain in the market, quality practices, eco-design, and optimization are also required.

Furthermore, the "SWARA approach" was employed to evaluate technology-oriented practice weights. Adopting technologies such as CPS and Digital Twins, which can provide flexibility to RMS, has the most weight [30]. The implementation of automation and robotics follows this. Later positions were occupied by the use of advanced material handling, additive manufacturing, remote monitoring, etc. As stated by [18], such advanced inventions can improve RMS performance by empowering decision-making and enhancing collaborations. Now, the advanced soft practices were analyzed, wherein the adoption of IoT and Cloud techniques were given the most weight. This is followed by the synchronization of AI & ML approaches, indicating the importance of software technologies for automation and flexibility in manufacturing, as discussed by [7]; [18]. Using system integration as well as simulation techniques, the adoption of cybersecurity in manufacturing, the penetration of BDA in existing systems, and the adoption of VR/AR in-process structure occupy the later positions in the SWARA analysis, indicating the relative importance of these practices in RMS adoption. A study carried by [30] supports these results wherein the importance was also given to these practices. Figure 4 depicts the computed weights for the chosen practices.

According to the sustainability oriented practices analysis, practices such as the execution of 10R approaches have the most weight [33], followed by the adoption of global standards and SDGs. Furthermore, environmentally conscious procedures like eco-friendly packaging materials, safety improvement initiatives, appointment of sustainability experts, and the execution of waste analysis were ranked at later positions, indicating the relative importance of these practices [30]. According to [7], CE is a paradigm shift for optimizing resource use and disposal of used materials, which can help to reduce production costs while improving RMS performance. The Eco-design and Optimization practices analysis using the SWARA technique resulted in first place for optimization of layout and infrastructure, demonstrating the importance of optimization practices related to layout and infrastructure as discussed by [44]. The weights of implementation of 4M practices, Ergonomical design practices, availability of optimization techniques, eco-design for material synthesis, and effective energy utilization and consumption indicate the importance of optimization practices, techniques, and optimized resources. Researchers [3]; [39] quoted that quality assurance procedures such as the adoption of Quality 4.0 are extremely important in the case of Industry 4.0 and CE; thus, occupied the topmost position during quality oriented practices analysis [30]. Employee education/training, the adoption of R and D activities, the monitoring of customer feedback and satisfaction, and supply chain collaboration, all of which were occupied in later positions, highlights the quality improvements through these practices.

Finally, the chosen performance metrics have been ranked employing the Pythagorean fuzzy CO-COSO technique. The Ki values are calculated and the ranking was obtained based on the Ki values as depicted in Figure 5.

The results show that production lead time was the most prominent performance metric for RMS because it is specifically adopted to respond changing customer needs [34]. Using several advanced technologies was ranked second because such technologies increase the flexibility of RMS [30]. The machine utilization rate was third, indicating effective use of available infrastructure, and manufacturing cost reduction using “Industry 4.0 technologies” along with “Circular economy practices” was fourth. Similar discussion was also observed in [28], which supports the current study’s findings. Waste reduction and profit percentage were ranked fifth and sixth, respectively, indicating that experts place nearly equal importance on waste management CE practices as they do on profit-making. Furthermore, sensitivity analysis shows the robustness of obtained results, implying 25% variations will not affect the study’s results. The results may assist managers in determining metrics’ significance levels as well as their relationship to the selected practices. It can help any industrial organization implement “Industry 4.0 technologies” and “Circular economy practices” in order to improve RMS acceptance; thus to measure performance.

5.2. Theoretical implications

The contributions made by presented research to theoretical enrichment are discussed in this section. o Advanced “Industry 4.0 technologies” and “Circular economy practices” were mentioned by several RMS researchers [1, 18]. Current research examines such articles to identify CE practices and develops a framework for them. This emphasizes the importance of CE in RMS adoption and performance enhancements. The identified CE practices, performance metrics, and analysis show that resources are valuable and cannot be substituted in any way. If resources are not handled carefully, industries may face a slew of problems in the future.

o Integrating "Industry 4.0 technologies" and "Circular economy practices" may help many manufacturing organizations enhance their performance. The presented study demonstrates the methodology for such integration as well as how to measure its effectiveness with the help of chosen performance metrics. The said nexus effect has the potential to lead to sustainable development and manufacturing.

o The presented work has the potential to provide a roadmap for sustainable manufacturing in the RMS domain by utilizing the identified technologies and practices. As a result, the study confirms the importance of CE practices in RMS sustainable development.

o The framework that was suggested indicates the use of SWARA and the "Pythagorean fuzzy COCOSO" method, which may improve performance in other similar domains of study. The study's findings add to the RMS research for adopting advanced "Industry 4.0 technologies" and "Circular economy practices", and chosen performance metrics for evaluating the impact of these practices.

o Study proposes a framework for implementing such practices as well as evaluating the impact of such practices on RMS performance using identified performance metrics.

5.3. Managerial implications

o The work presented enables managers recognize benefits in incorporating "Industry 4.0 technologies" and "Circular economy practices" in RMS.

o Managers may also find how the selected practices affect RMS performance based on the study's findings. Let us consider, because production lead time has been prioritized at the top in performance metrics, managers can reduce production lead time by implementing the identified practices.

o Understanding the benefits of the selected technologies and practices, a great organization could extend support for their adoption to increase business profits and also to compete in the market. This can also help with decision-making at various stages of implementation.

o The framework developed can be used as a guide for gradually adopting "Industry 4.0 technologies" and "Circular economy practices". Research may additionally decrease likelihood of implementation failure while improving RMS performance.

o This research reveals that managers must develop a strategic plan for RMS performance improvement and sustainable development by implementing identified practices. This framework now assists in long-term strategic planning.

o Our findings also show a cause-and-effect relationship between selected practices and RMS performance parameters. This can help managers identify the source of poor performance by linking performance parameters to the chosen practices.

5.4. Implications for researchers and practitioners

This section talks about the study's potential effects on both scholars and practitioners.

o This study highlights the necessity of more study regarding this topic to enhance RMS adoption. The researchers can delve deeper into each practice and devise a strategy for its successful implementation in industry.

o The suggested framework can help practitioners apply the “Industry 4.0 technologies” in organizations. Using current framework, practitioners are able to formulate a systematic plan to implement “Circular economy practices” which will eventually contribute to environmentally friendly manufacturing.

o Practitioners can now evaluate the RMS based on the identified performance metrics and determine the cause of any poor performance in the organization. For example, if the production lead time is increased, practitioners can now determine whether more advanced technology, soft practices, etc. are required, or if any technology is malfunctioning.

o The investigators may utilize the demonstrated technique in different domains to enhance performance and promote sustainable growth. Researchers may also conduct additional research on practices in their areas of study to investigate implementation perspectives.

o Practitioners can figure out the corresponding significance of performance metrics by prioritizing them and developing implementation plans accordingly. For example, efforts must be made to reduce lead time when compared to the use of renewable energy so that the organization’s overall performance can be improved.

o Because the top five performance metrics are critical for RMS performance, practitioners can use this framework to improve and maintain them in actual practice. This can help to improve RMS performance and keep the organization competitive in the market.

5.5. Implications to cope with post Covid-19 pandemic scenario

The pandemic outbreak has disturbed industrial operations as well as the entire supply chain. Additionally, due to pandemic, consumer demands have significantly changed, necessitating the development of a route map for the repurposing of production activities [15]. In the following ways, the developed framework can assist during repurposing.

o Because of its flexibility, the RMS has the ability of fulfilling changing customer needs, and thus it can meet the requirements of the Covid-19 outbreak situation to a large extent.

o The developed framework may help manufacturing organizations for maintaining and enhancing performance under a dynamic and disrupted market environment.

o Because the framework provides a roadmap for implementing “Industry 4.0 technologies”, it may help to withstand this dynamic situation.

o The developed framework also provides guidelines for shortening lead time as well as manufacturing costs. As a result, when the world is facing an economic crisis, the framework can assist in cost reduction. Thus, the developed framework assists in the delivery of low-cost products to customers in the shortest possible time.

o Furthermore, the framework facilitates the insertion of “Industry 4.0 technologies” into manufacturing facilities to boost efficiency. This use of “Circular economy practices” during manufacturing can also lead to environmentally friendly production.

o The listed performance metrics and their ranking may allow the governing authorities to assess the manufacturing system and, hence, grant the necessary permissions.

o The authorities can assess the RMS’s environmental friendliness and utility in a post-pandemic situation. In practice, the framework may be extremely useful in meeting the needs of today’s scenario and guiding decision-makers.

o As a result of the pandemic situation, there is a significant increase in demand for medical-related equipment and products. Because RMS and the developed framework are capable of scaling the volume and variety of production, it is capable of meeting such demands that can assist in the required treatment of patients.

o Automation and robotics can help in manufacturing operations without human intervention and touch, which can help reduce the virus infections during pandemic.

o Furthermore, practices such as remote monitoring and sensing can enable manufacturing operations to be carried out from a distance/from one's home while keeping supply chains unaffected.

o Practices such as R and D may enable the development and manufacture of products such as sanitizer bottles, which are in great demand due to pandemic situation. This may assist people deal with a pandemic situation.

6. Conclusion and Future Scope

An existing article's study was used in this research for finding "Industry 4.0 technologies" and "Circular economy practices". This has also revealed a collection of performance metrics which may be used to assess the efficacy of these technologies and practices in RMS adoption. Furthermore, a SWARA technique was employed examine importance of chosen practices, and performance metrics were ranked using "Pythagorean fuzzy COCOSO" technique and expert advice. According to obtained results, the selected technologies and practices are beneficial for improving RMS performance. The dynamic and drastically changed customer needs resulted due to pandemic can also be met by utilizing the reconfigurability and flexibility of RMS. This can help conquer the issues raised by the worldwide outbreak, maintain the supply chain, and provide products at the most affordable price. The identified performance metrics as well as prioritization may also assist organizations evaluate current state of RMS and make attempts to improve it with the help of selected practices. The identified CE practices, on the other hand, can help manufacturing organizations progress toward sustainable development while also lowering product manufacturing costs. The developed framework have the potential to be extremely beneficial for the adoption of advanced technologies and CE practices in RMS, which can increase productivity, flexibility, reconfigurability, and environmentally friendly manufacturing processes. The most effective practices for cost savings and lowering manufacturing costs are optimization, waste minimization, careful resource consumption, employee training, etc. As a result, the presented study can assist in dealing with pandemic situations. This study, based on extensive research, has limitations due to its reliance on expert opinion and potential bias. Future research could involve a larger survey with a wider range of experts to develop a more detailed framework. The assumption-based steps could be addressed by considering actual case studies. The study could be expanded to include medical equipment and product manufacturing companies, enhancing performance and addressing the Covid-19 pandemic. Each practice can be thoroughly examined and a detailed implementation plan developed.

References

[1] Abdi, M. R., Labib, A., Edalat, F. D., and Abdi, A. Rms performance evaluation using anp and holonic structure. In

Integrated Reconfigurable Manufacturing Systems and Smart Value Chain. 2018, pp. 197–215.

[2] Ayyildiz, E., and Taskin Gumus, A. Interval-valued pythagorean fuzzy ahp method-based supply chain performance evaluation by a new extension of scor model: Scor 4.0. *Complex and Intelligent Systems 7*, 1 (2021), 559–576.

[3] Bag, S., Gupta, S., and Kumar, S. Industry 4.0 adoption and 10r advance manufacturing capabilities for sustainable development. *International Journal of Production Economics 231* (2021), 107844.

[4] Balan, G. S., Kumar, V. S., and Raj, S. A. Machine learning and artificial intelligence methods and applications for post-crisis supply chain resiliency and recovery. *Supply Chain Analytics 10* (2025), 100121.

[5] Bortolini, M., Botti, L., Galizia, F. G., and Regattieri, A. Bi-objective design and management of reconfigurable manufacturing systems to optimize technical and ergonomic performances. *Applied Sciences 11*, 1 (2021), 1–14.

[6] Dahmani, N., Benhida, K., Belhadi, A., Kamble, S., Elfezazi, S., and Jauhar, S. K. Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework. *Journal of Cleaner Production 320* (2021), 128847.

[7] Dantas, T. E. T., Destro, I. R., Hammes, G., Rodriguez, C. M. T., and Soares, S. R. How the combination of circular economy and industry 4.0 can contribute towards achieving the sustainable development goals. *Sustainable Production and Consumption 26* (2021), 213–227.

[8] Dou, J., Li, J., Xia, D., and Zhao, X. A multi-objective particle swarm optimisation for integrated configuration design and scheduling in reconfigurable manufacturing system. *International Journal of Production Research 59*, 13 (2021), 3975–3995.

[9] Gupta, H., Kumar, A., and Wasan, P. Industry 4.0, cleaner production and circular economy: An integrative framework for evaluating ethical and sustainable business performance of manufacturing organizations. *Journal of Cleaner Production 295* (2021), 126253.

[10] Gupta, N., Garg, P., and Ahuja, N. An integrated pythagorean fuzzy delphi-ahp-cocoso approach for exploring barriers and mitigation strategies for sustainable supply chain in the food industry. *Supply Chain Analytics 10* (2025), 100105.

[11] Keršuliene, V., Zavadskas, E. K., and Turskis, Z. Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (swara). *Journal of Business Economics and Management 11*, 2 (2010), 243–258.

[12] Khezri, A., Benderbal, H. H., and Benyoucef, L. Sustainable reconfigurable manufacturing system design: A multi-objective approach. *International Journal of Production Research 58*, 7 (2020), 2020–2036.

[13] Koren, Y., Gu, X., and Guo, W. Reconfigurable manufacturing systems: Principles, design, and future trends. *Frontiers of Mechanical Engineering 13*, 2 (2018), 121–136.

[14] Kruger, K., and Basson, A. Erlang-based holonic controller for a palletized conveyor material handling system. *Computers in Industry 101* (2018), 120–126.

[15] López-Gómez, C., Corsini, L., Leal-Ayala, D., and Fokeer, S. Covid-19 critical supplies: The manufacturing repurposing challenge. Tech. rep., United Nations Industrial Development Organization (UNIDO), 2020.

[16] Maganha, I., Silva, C., and Ferreira, L. M. D. F. The layout design in reconfigurable manufacturing systems: A literature review. *The International Journal of Advanced Manufacturing Technology 105*, 1–4 (2019), 683–700.

[17] Mondello, A., Salomone, R., and Mondello, G. Exploring circular economy in the cosmetic industry: Insights from a literature review. *Environmental Impact Assessment Review 105* (2024), 107443.

[18] Morgan, J., Halton, M., Qiao, Y., and Breslin, J. G. Industry 4.0 smart reconfigurable manufacturing machines. *Journal of Manufacturing Systems 59* (2021), 481–506.

[19] Mosallanezhad, B., Smith, N. R., Gholian-Jouybari, F., and Hajiaghaei-Keshteli, M. An optimization framework for emergency supply chains prioritizing elderly populations during pandemics. *Supply Chain Analytics 11* (2025), 100131.

[20] Mourtzis, D., Papatheodorou, A. M., and Fotia, S. Development of a key performance indicator assessment methodology and software tool for product-service system evaluation and decision-making support. *Journal of Computing and Information Science in Engineering 18*, 4 (2018), 1–13.

[21] Ojiaku, O. C., Nwaizugbo, I. C., and Osarenkhoe, A. Role of brand familiarity on the influence of electronic word-of-mouth and customers' behavioral intentions. *International Journal of Innovation and Technology Management 21*, 6 (2024), 1–24.

[22] Ongena, G., Morsch, P., and Ravesteijn, P. Digital leadership competency to enhance digital transformation. *International Journal of Innovation and Technology Management 21*, 6 (2024).

[23] Orejuela, S., Johansson, G., and Motte, D. Examining the implications of knowledge boundaries for a large-scale agile transformation initiative of a manufacturing company. *International Journal of Innovation and Technology Management 21*, 5 (2024), 1–25.

[24] Oyefusi, O. N., Enegbuma, W. I., Brown, A., and Olanrewaju, O. I. Development of a novel performance evaluation framework for implementing regenerative practices in construction. *Environmental Impact Assessment Review 107* (2024), 107549.

[25] Palsodkar, M., Yadav, G., and Nagare, M. An agile new product development-based sustainable supply chain framework to improve environmental quality performance: emerging economies perspective. *Management of Environmental Quality: An International Journal 34*, 3 (2023), 565–588.

[26] Palsodkar, M. A., Nagare, M. R., and Narwane, V. S. Exploratory analysis of factors influencing agile new product development adoption in manufacturing industries. *International Journal of Innovation and Technology Management 21*, 3 (2024).

[27] Pansare, R., and Yadav, G. Repurposing production operations during covid-19 pandemic by integrating industry 4.0 and reconfigurable manufacturing practices: An emerging economy perspective. *Operations Management Research 15* (2022), 1270–1289.

[28] Pansare, R., Yadav, G., Garza-Reyes, J. A., and Nagare, M. R. Assessment of sustainable development goals through industry 4.0 and reconfigurable manufacturing system practices. *Journal of Manufacturing Technology Management 34*, 3

(2023), 383–413.

[29] Pansare, R., Yadav, G., and Nagare, M. Reconfigurable manufacturing system: A systematic review, meta-analysis and future research directions. *Journal of Engineering, Design and Technology 21*, 1 (2023), 228–265.

[30] Pansare, R., Yadav, G., and Nagare, M. R. A hybrid framework to prioritize the performance metrics of reconfigurable manufacturing system (rms) using fuzzy ahp–topsis method. *The International Journal of Advanced Manufacturing Technology 124* (2022), 863–885.

[31] Pansare, R., Yadav, G., and Nagare, M. R. Integrating operational excellence strategies with industry 4.0 technologies through reconfigurable manufacturing system practices. *The TQM Journal* (2022).

[32] Pansare, R., Yadav, G., and Nagare, M. R. Reconfigurable manufacturing system: A systematic bibliometric analysis and future research agenda. *Journal of Manufacturing Technology Management 33*, 3 (2022), 543–574.

[33] Pansare, R., Yadav, G., Nagare, M. R., and Jani, S. Mapping the competencies of reconfigurable manufacturing system with the requirements of industry 4.0. *Journal of Remanufacturing 12* (2022), 385–409.

[34] Pansare, R. B., and Nagare, M. R. Exploring the significant factors of reconfigurable manufacturing system adoption in manufacturing industries. *Journal of Modelling in Management* (2023).

[35] Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., and Terzi, S. Assessing relations between circular economy and industry 4.0: A systematic literature review. *International Journal of Production Research 58*, 6 (2020), 1662–1687.

[36] Sanchez, M., Exposito, E., and Aguilar, J. Industry 4.0: Survey from a system integration perspective. *International Journal of Computer Integrated Manufacturing 33*, 10 (2020), 1017–1041.

[37] Shivajee, V., Singh, R. K., and Rastogi, S. Manufacturing conversion cost reduction using quality control tools and digitization of real-time data. *Journal of Cleaner Production 237* (2019), 117678.

[38] Xu, J., Zhou, L., He, G., Ji, X., Dai, Y., and Dang, Y. Comprehensive machine learning-based model for predicting compressive strength of ready-mix concrete. *Materials 14*, 5 (2021), 1–18.

[39] Yadav, G., Luthra, S., Huisingh, D., Mangla, S. K., Narkhede, B. E., and Liu, Y. Development of a lean manufacturing framework to enhance its adoption within manufacturing companies in developing economies. *Journal of Cleaner Production 245* (2020), 118726.

[40] Yadav, G., Luthra, S., Jakhar, S. K., Mangla, S. K., and Rai, D. P. A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case. *Journal of Cleaner Production 254* (2020), 120112.

[41] Yadav, G., Mangla, S. K., Luthra, S., and Jakhar, S. Hybrid bwm-electre-based decision framework for effective offshore outsourcing adoption: A case study. *International Journal of Production Research 56*, 18 (2018), 6259–6278.

[42] Yazdani, M., Zarate, P., Zavadskas, E. K., and Turskis, Z. A combined compromise solution (cocoso) method for multi-criteria decision-making problems. *Management Decision 57*, 9 (2019), 2501–2519.

[43] Yelles-Chaouche, A. R., Gurevsky, E., Brahimi, N., and Dolgui, A. Reconfigurable manufacturing systems from an optimisation perspective: A focused review of literature. *International Journal of Production Research* (2020), 1–19.

[44] Youssef, A. M. A., and Elmaraghy, H. A. Availability consideration in the optimal selection of multiple-aspect rms configurations. *International Journal of Production Research 46*, 21 (2008), 5849–5882.

[45] Zahid, A., Leclaire, P., Hammadi, L., Costa-Affonso, R., and El Ballouti, A. Exploring the potential of industry 4.0 in manufacturing and supply chain systems: Insights and emerging trends from bibliometric analysis. *Supply Chain Analytics 10* (2025), 100108.