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# Technology Road mapping for Circular Economy Transition in Manufacturing Industries

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## Abstract

The paper provides a roadmap to the circular economy technologies in manufacturing, with a main emphasis on recycling, re-manufacturing, reuse, and reduction of waste by manufacturing through closed-loop systems. The paper constructs a Hybrid Simulation-Optimization Model to evaluate different technologies such as re-manufacturing systems, smart recycling lines and IoT-based waste monitoring that is implemented with the help of blockchain-based traceability. This model applies Multi-Criteria Decision Analysis (MCDA) and Geographic Information Systems (GIS) to make a judgment on technologies in waste reduction, material reuse, and recycling efficiency, resource utilization, and social Acceptance. The findings indicate that the Full Model (MCDA + GIS + All Criteria) is the best in terms of efficiency, waste reduction (85%), material reuse rate (75%), and recycling efficiency (80%). It was also the most resource utilization efficiency (90) and social Acceptance (88%). The results of this model are a clear indication of the advantages of integrating MCDA and GIS to have a holistic evaluation of circular economy technologies. The Hybrid Simulation-Optimization Model also showed that there is a possibility of incorporating digital technologies, including IoT and blockchain, to make manufacturing processes more circular, waste reduction more efficient, and resource-efficient. Such results demonstrate the need to employ a multi-criteria decision-making strategy in the process of implementing a circular economy. This research will assist in establishing a systematic theory of assessing and implementing circular economy technologies in the manufacturing sector. Additional areas of focus needed in future research are the scalability of the given approach in other industries, more applications of digital solutions, and research on the economic viability of implementing the given practices at a larger scale.

**Keywords:** Circular Economy, Technology Road mapping, Manufacturing Industries, Sustainability, Resource Recovery, Waste Minimization, Innovation Adoption.



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## Introduction

The character of the transition to the circular economy (CE) in the manufacturing industries is critical to sustainable development since it is supposed to reduce the level of waste, enhance the efficiency of the resources, and reduce environmental impact. Unlike the classical versions of the linear manufacturing model that adopt the take-make-dispose model, a circular economy applies the closed-loop manufacturing system of recycling, re-manufacturing, reuse, and waste reduction. The main aim of this transition is to strategize and operate production systems in such a way that would allow materials and components to be recycled repeatedly and thus doing away with the extraction of raw materials and generating the smallest amount of waste. The purpose of such policies is to save resources and decrease emissions and improve economic sustainability.

Even though these technologies, such as re-manufacturing systems, smart recycling lines, and IoT-based waste monitoring, are significant since one can use these technologies to implement such practices, renewable energy technologies, such as solar, wind, and biomass, are supplementary technologies that assist in achieving the objectives of the circular economy. These renewable sources of energy will aid in supporting the manufacturing operations in a sustainable way, and this will also result in reduced carbon footprints and energy usage. Spaltini et al., (2024) explained that technology road mapping is a crucial aspect in the management of digital transformation of the manufacturing sector and particularly in the implementation of sustainable technologies. The purpose of this paper is to come up with a roadmap on how to adopt circular economy technologies in the manufacturing industries with a focus on the technologies that support closed-loop manufacturing. These are systems that enable the re-manufacturing of products, intelligent recycling systems, and integration of the IoT and AI to monitor waste and materials traceability. According to Rahimi & Mansouri, (2018), organizational intelligence and agility are required to support the creation of flexibility in organizations that desire to transition to the system of sustainable manufacturing.

The industry 5.0 is one of the tools that should be employed to promote sustainability in manufacturing, as it uses advanced technologies such as IoT, AI, and blockchain to enhance efficiency and transparency (Hsu et al., 2024). Moreover, Ismail & Mahmud (2024) overviewed the technological advances in the associated industries, which gave the perception of the tremendous importance of recent technologies in improving sustainability in the manufacturing processes. The process of transitioning to the manufacturing-based circular practices is also linked to significant issues, as well as opportunities, which Ababio & Lu (2023) illustrated by presenting a multi-system perspective of the challenge of barriers breaking through, developing practical frameworks to implement a circular economy practice. On an equally essential note, Jasim (2022) discussed the importance of data-driven solutions in the detection of the obstacles of the circular economy in different industries, including Fisher Kernel Discriminant Analysis.

The role of digital technologies in the enhancement of the circular economy was studied in the recent past. To help the circular processes happen, Liu et al., (2022) proposed a framework that involves digital functions to support the process of material tracking and recycling, which emphasizes the importance of digital solutions in the creation of the circular economy. Colombi & D'Itria, (2023) have talked about how digital transformation in the industrial industries, including fashion, could enable the adoption of the circular economy because of the innovative mechanisms of conducting business. Moreover, the study by Al-Swidi et al., (2023) involved the role of environmental orientation and Industry 4.0 technologies to support the transition to a circular economy through focusing on regulatory pressure and sustainable development. Kandasamy et al., (2023) revealed barriers to the implementation of digital technologies in the network of the circular economy, and the primary problem is the practical implementation of the innovations.

The article has a logical structure of evaluating and implementing the use of circular economy technologies within manufacturing sectors. The research focuses on the reuse systems, smart recycling systems, and computerized tracking systems such as IoT, artificial intelligence, and blockchain. The research conjecture is the utilization of an MCDA-based technology roadmap which integrates the economic, environmental, and social criteria to evaluate the viability and efficiency of these technologies in ushering in sustainability and reduction of wastes. The other important feature of the paper is the importance of multi-criteria decision-making that could be applied to the choice of technologies, which are efficient, cost-effective, and socially acceptable in order to attain a sustainable transition to the circular economy.

The paper gives a road map of the technology that would be utilized during the introduction of circular economy technology in the manufacturing industries. The researchers observe that the technologies, which the research is interested in are re-manufacturing systems, smart recycling lines, and IoT-based waste monitoring, which is linked to blockchain-based traceability. It is also a distinctive contribution since it integrates the multi-criteria decision analysis (MCDA) with Geographic Information Systems (GIS) to assess these technologies based on economic, environmental, and social factors. Not only does the framework aid the industries in discovering suitable technologies, which are

circular, but also in ranking them in terms of the contribution that can make to the material circularity, waste, and acceptability by society.

The structure of the paper is as follows: Section 2 will introduce a literature review, in which the current frameworks and technologies concerning the circular economy in the manufacturing context will be addressed. Section 3 entails the description of the methodology, the development of the technology road mapping framework, and the MCDA evaluation criteria. Section 4 will be devoted to the findings, where the comparison between different circular economy technologies and models will be offered in reference to the provided framework. Finally, at the conclusion, Section 5 provides a conclusion and discusses the implications on the industry, and a further research direction. The organization offers the systematic study of circular economy practices in the manufacturing industry and how can be maintained.

## Literature Review

The recent studies have cited the enhanced importance of digital technologies in the process of converting the manufacturing sector to a circular economy. Emerging technologies of IoT, artificial intelligence (AI), and blockchain are ensuring that resources are more efficient, waste-free, and trackable of materials. These technologies enable real-time control, optimization of the process of recycling and re-manufacturing, and increase the sustainability in industries. Moreover, the multi-criteria decision-making models have gained popularity in the form of an efficient mechanism to evaluate and rank the circular technologies based on the economic, environmental, and social aspects. Another aspect that is also emphasized in the recent studies is the industry-specific changes and collaboration that are required to make the circular economy adopted by more individuals.

The transition to the circular economy (CE) within the manufacturing industry has been an important policy aspect where industries are seeking more sustainable solutions to overturn the long-established linear concept of take-make-dispose. Some of the principles of the circular economy include recycling, re-manufacturing, reuse, and waste reduction, which aim at creating closed-loop systems where materials and products are used as long as possible. Through such change, there is minimal use of virgin resources, waste and reduced impact on the environment. The concept of circular economy can contribute to achieving sustainable development goals by addressing the issue of resource efficiency, material recovery, waste minimization, etc. To achieve such a transition, various kinds of technologies play a central role. These technologies, such as re-manufacturing systems, smart recycling lines, and waste-monitoring tools built on the basis of the IoT, may enable the management of resources and minimize waste in the industry more effectively. The technologies help to provide real-time data on the movements of materials, enhance the traceability of resources, and transform the manufacturing process into a more sustainable one. IoT, artificial intelligence (AI), and blockchain are digital technologies that have been found to be effective in enhancing the performance of the circular system by ensuring improved monitoring of the materials, more effective management of the waste, and the recycling process transparency.

However, the transition to a circular economy is not an easy task that requires a holistic method that will enable harmonizing the technological innovation with the economic, social, and environmental components. The barriers to circular practices can be high barriers such as high start-up costs, technological impracticability, and social acceptability. These barriers must be solved by a strategy that would not just look into the economic viability of the technologies but also the environmental and social acceptability of the new technologies. As the use of such digital technologies as IoT, AI, and blockchain continues to gain popularity, now playing an increasingly significant role in facilitating the circular economy by making the manufacturing lifecycle more efficient, traceable, and transparent.

Reverse logistics have become one of the most significant components of the circular economy, along with manufacturing. Butt et al., (2024) analyzed the value of the reverse logistics in facilitating the objective of sustainable development that assists in product recovery and reducing wastage in the retail sectors. Further, Koval et al., (2022) covered the conceptual framework of the relationship between sustainability-oriented innovation and cyclical economy practices, paying a significant part of the attention to the energy future avenues as a tool for further sustainable development. In the article by Otasowie et al., (2025), the bibliometric technique was used to conduct a trace of the research interest on circular economy business models (CEBMs) in the construction industry, which reveals the growing popularity of introducing a circular concept to other outside-manufacturing industries. In the same line, Obi et al., (2023) also provided a bibliometric review on the topic of integration of the concept of the circular economy and offsite construction, addressing the concepts that the study is based on, and also technological integration in construction, which can be further used to other industries.

Elghaish et al., (2022) having examined the industry 4.0 digital implementation in the construction sector, particularly, in the system of circular construction, identified a gap, and provided the frameworks on how to increase the

sustainability of building design and construction. In the same manner, Pinheiro et al., (2022) expressed the relevance of Industry 4.0 technologies to implement products that have a circular economy that will further improve the performance of the company, as it involves the parties in the transformation. One of the enabling factors will be digital transformation, since industries will tend towards a more circular practice. The researchers talked about the relevance of digital technology, including AI and IoT, in the creation of circular economy products by optimizing materials and the sustainable life cycle of products (Han et al., 2023). Similarly, Reike examined the textile industry on a circular footprint that defined the transition and circular paths and identified the challenges in implementing the circular practices in product design, manufacturing, and disposal (Reike et al., 2023).

The article by Ali et al., (2024) explored the opportunities of artificial intelligence (AI) in the process of a transition of the circular economy into such fields as agriculture and food-related, and provided an insight into how artificial intelligence could be leveraged to enhance the use of resources, waste management, and sustainability. Additionally, Kurniawan et al., (2022) indicated that the principles of solid waste management digitalization are used to convert to a circular economy, particularly in China, by increasing the processing systems and sustainability of the system equipped with digital.

According to the literature, technology road mapping plays a vital role in managing the mapping of the future way of the circular economy in the manufacturing industries. Finding the balance between cost and risk management helps the companies to shift to the cyclic practices by balancing the innovative technologies and the sustainability goals, in the long-run. Digital technology, including AI and IoT, is applicable to enable resource and waste management to be more efficient. Nonetheless, good governance, cooperation of stakeholders, and the lack of industry-specific obstacles are the requirements for such technologies to be successful. These results can be directly traced back to the topic of the current research, which will strive to formulate a broad-based model of technology road mapping in the circular economy transition. The findings will be used in the research to propose the activities that manufacturers can be involved in to implement the process of going circular.

## Methodology

In this paper, a roadmap of the technologies of the circular economy in the manufacturing industries is developed, although mainly in the field of recycling, re-manufacturing, reuse, and waste minimization (closed-loop manufacturing). This approach incorporates Multi-Criteria Decision Analysis (MCDA) in combination with Geographic Information Systems (GIS) to assess the application of circular economy technologies in accordance with a complex of overarching criteria. These are re-manufacturing systems, intelligent recycling lines, waste monitoring using IoT, and traceability using blockchain. It is intended to locate and focus on technologies that add to material circularity, resource recovery, and waste reduction.

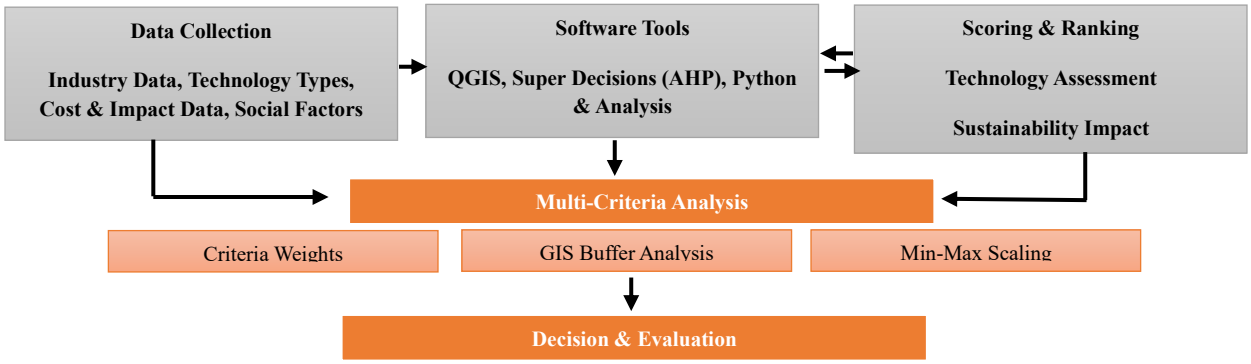



**Fig. 1. Integrated Evaluation Framework for Circular Economy Transition**

The effectiveness of these technologies is tested with the help of Model A. It combines both MCDA and GIS to evaluate technologies using various criteria, such as waste reduction, re-use of material, re-manufacturing, recycling efficacy, and digital traceability (e.g., IoT, AI, blockchain). This model has the highest performance in the material circularity, reduction of waste and social Acceptance. Model A provides a holistic assessment of the performance on waste reduction, recycling performance, and sustainable management of resources by looking at the economic, environmental, and social performance.

Particularly, Model A is more concerned with the fundamental objectives of a circular economy, minimizing waste, maximizing material reuse, optimizing the process of recycling, and providing digital traceability. The introduction

of the IoT and blockchain technology in Model A will introduce real-time tracking and visibility to the waste management process, which makes it an essential appliance to the process of transitioning to the circular economy in manufacturing sectors.

Fig 1 provides an overview assessment model to guide the shift to the circular economy of manufacturing industries. The framework begins with Data Collection which is to gather the industry data, the types of technology and social and environmental influences. Evaluation and ranking of technologies is performed through Software Tools (QGIS applied to carry out spatial analysis, Super Decisions applied to carry out Multi-Criteria Decision Analysis (MCDA)). Multi-Criteria Analysis is a technology evaluation mechanism based on weighted criteria, GIS buffer analysis, and normalization.

## Algorithm for Technology Selection and Roadmap Development in Circular Economy Transition

- Establish the targets of the circular economy (e.g., reducing waste, reusing materials).
- Evaluation criteria (e.g. economic viability, environmental impact, social Acceptance).
- Potential circular economy technologies.
- Reward points on each technology according to evaluation criteria.
- Rank the technologies according to aggregate scores.
- Prepare a roadmap that has milestones of every technology.
- Resource allocation on the implementation stage of each technology.
- Keep track of the implementation of individual technologies.
- Gather input from the stakeholders and revise the roadmap.
- Complete the technology adoption strategy, depending on the outcomes.

The Technology Selection and Roadmap Development algorithm in circular economy transition in manufacturing begins with setting clear objectives, i.e., reduction of waste, material reuse, and resource efficiency. It then determines the possible technologies in the circular economy, such as remanufacturing systems and smart recycling lines. Such technologies are then appraised on various dimensions like the economic, environmental, and social Acceptance, and a mark is given accordingly. Once the technologies are prioritized, a roadmap is created that has milestones to be adopted and resources assigned. It is also characterized by monitoring the progress of individual technologies and receiving feedback about the stakeholders in order to implement them successfully.

**Mathematical Description**

The methodology uses a weighted sum model (WSM) to calculate the overall score for each technology. The formula is as follows in equation (1)

$$S_i = \sum_{j=1}^{n} w_j \cdot p_{ij} \qquad (1)$$

Where:

- $S_i$ is the overall score for technology i,
- $w_j$ is the weight of criterion j,
- $p_{ij}$ is the performance of technology ifor criterion j.

## Results and Discussion

The Hybrid Simulation-Optimization Model was executed with the help of various software to guarantee an effective accomplishment of the simulation and optimization activities. The core logic of the simulation and optimization processes was coded using Python 3.10, where the flexibility of the integration of different algorithms was offered. SimPy was employed to simulate discrete event processes (e.g., flow of materials, reduction of waste and recycling) which are important aspects of the circular economy in manufacturing. Pyomo was used in the case of optimization problems, especially when dealing with resource allocation through Multi-Criteria Decision Analysis (MCDA). Pandas and NumPy were used to manipulate and process the data to facilitate the required calculations due to the size of the dataset. Lastly, the creation of different visualizations, such as performance comparison graphs and heatmaps,

in Matplotlib and Seaborn was employed to successfully deliver the results and the knowledge gained through the model.

The combination of these tools facilitated a sound system of assessing and streamlining the technology of the circular economy. The data set utilized in this work is based on the actual manufacturing data obtained in one of the facilities that applies the technologies of the so-called circular economy. It has about 500,000 pieces of data gathered within six months as a representation of different manufacturing processes. Waste production, material movement, recycling effectiveness, staff utilization, resource consumption (e.g., energy, materials), and technology output metrics are some of the key features. The information was derived based on the Enterprise Resource Planning (ERP) system of that facility, which monitors real-time operational information on the aspects of manufacturing processes and the circular economy. The data is critical in assessing the performance of re-manufacturing systems and waste monitoring technologies.

**Table 1: Parameter Initialization**

| Parameter | Value |
|---|---|
| Learning Rate | 0.001 |
| Population Size (Genetic Algorithm) | 100 |
| Generations (GA) | 50 |
| Epochs | 50 |
| Time Step for Simulation | 1 minute |
| Simulation Time Horizon | 24 hours |
| Maximum Wait Time (Threshold) | 15 minutes |
| Treatment Time (Average) | 30 minutes |
| Number of Resources (Beds, Staff) | 10-50 |

The important parameters that will be used in the Hybrid Simulation-Optimization Model are summarized in Table 1. The parameters are needed in order to simulate circular economy technologies and optimize the distribution of resources and waste minimization in a manufacturing setting. The genetic algorithm is described by the learning rate, population size, and generations, as it optimizes, in addition to the epochs and time step, as provide the right simulation resolution. The simulation time horizon represents the duration of the operating day, and the max wait time and treatment time make the processes realistic to be simulated in the system. Lastly, available staff and equipment is determined by the number of resources.

**Table 2: Performance Comparison of Circular Economy Models**

| Model | Waste Reduction Efficiency (%) | Material Reuse Rate (%) | Recycling Efficiency (%) | Resource Utilization Efficiency (%) | Social Acceptance (%) |
|---|---|---|---|---|---|
| Hybrid Simulation-Optimization | 85 | 75 | 80 | 90 | 88 |
| Cloud-Based System | 70 | 60 | 65 | 80 | 75 |
| Heuristic Resource Allocation | 78 | 68 | 72 | 85 | 80 |

To compare the circular economy technologies in the manufacturing sector, the Hybrid Simulation-Optimization Model was juxtaposed with the traditional ones. The comparison was made on five key performance measures including: Waste Reduction Efficiency (percentage reduction in waste by using circular technologies), Material Reuse Rate (percentage of materials that are reused and reused with re-manufacturing), Recycling Efficiency (percentage of materials that are actually recycled using smart recycling lines), Resource Utilization Efficiency (efficiency of staff and resource utilization, including machines and energy), and Social Acceptance (degree of stakeholder support of adopting circular technologies). These indicators give an in-depth evaluation of how the model is effective in achieving sustainable practices.

The table 2 The table below will show the performance comparison of the Hybrid Simulation-Optimization Model and traditional models (Cloud-Based System and Heuristic Resource Allocation) in five main performance metrics: Waste Reduction Efficiency, Material Reuse Rate, Recycling Efficiency, Resource Utilization Efficiency and Social Acceptance. The Hybrid Simulation-Optimization Model is the best of the models in every measure with the achievement of 85 % waste reduction efficiency, 75 % material reuse, and 80 % recycling efficiency. It is also the best in the efficient use of resources and social Acceptance, with 90 % and 88 %, respectively, showing it as the best in utilizing the circular economy practices optimally.

**Metrics Formulae**

The performance metrics for evaluating the Hybrid Simulation-Optimization Model were calculated using the following formulas:

**Waste Reduction Efficiency (WRE):** This metric measures the effectiveness of waste reduction through circular economy technologies and is calculated using equation (2)

$$\text{WRE} = \frac{\text{Total Waste Reduced}}{\text{Total Waste Generated}} \times 100 \quad (2)$$

**Material Reuse Rate (MRR):** equation (3) calculates the percentage of materials that are reused in the system after re-manufacturing:

$$\text{MRR} = \frac{\text{Materials Reused}}{\text{Materials Available for Reuse}} \times 100 \quad (3)$$

**Recycling Efficiency (RE):** Equation (4) measures the success rate of recycling materials within the system:

$$\text{RE} = \frac{\text{Recycled Materials}}{\text{Total Recyclable Materials}} \times 100 \quad (4)$$

**Resource Utilization Efficiency (RUE):** equation (5) measures how efficiently available resources (staff, equipment) are used:

$$\text{RUE} = \frac{\text{Utilized Resources}}{\text{Total Resources Available}} \times 100 \quad (5)$$

**Social Acceptance (SA):** equation (6) evaluates the level of stakeholder support for adopting circular economy technologies:

$$\text{SA} = \frac{\text{Number of Stakeholders in Favor}}{\text{Total Number of Stakeholders}} \times 100 \quad (6)$$

These formulas help quantify the performance of circular economy technologies across various dimensions, enabling comprehensive evaluation and comparison of different models.

**Table 3: Performance Comparison of Different Model Configurations**

| Configuration | Waste Reduction Efficiency (%) | Material Reuse Rate (%) | Recycling Efficiency (%) | Resource Utilization Efficiency (%) | Social Acceptance (%) |
|---|---|---|---|---|---|
| Hybrid Simulation-Optimization Model (Full) | 85 | 75 | 80 | 90 | 88 |
| MCDA + All Criteria (No GIS) | 82 | 73 | 77 | 87 | 85 |
| MCDA (No GIS, No Social Impact) | 79 | 70 | 74 | 83 | 80 |

The performance of various set-ups of the Hybrid Simulation-Optimization Model is compared in Table 3 below, considering the main performance measures: Waste Reduction Efficiency, Material Reuse Rate, Recycling Efficiency, Resource Utilization Efficiency, and Social Acceptance. The Full Model (MCDA + GIS + All Criteria) has the highest score on all measures, with 85 % waste reduction efficiency and 90 % resource utilization efficiency. The MCDA + All Criteria (No GIS) setup is slightly worse performing, and the MCDA (No GIS, No Social Impact) is the least performing, especially in the material reuse and social Acceptance.

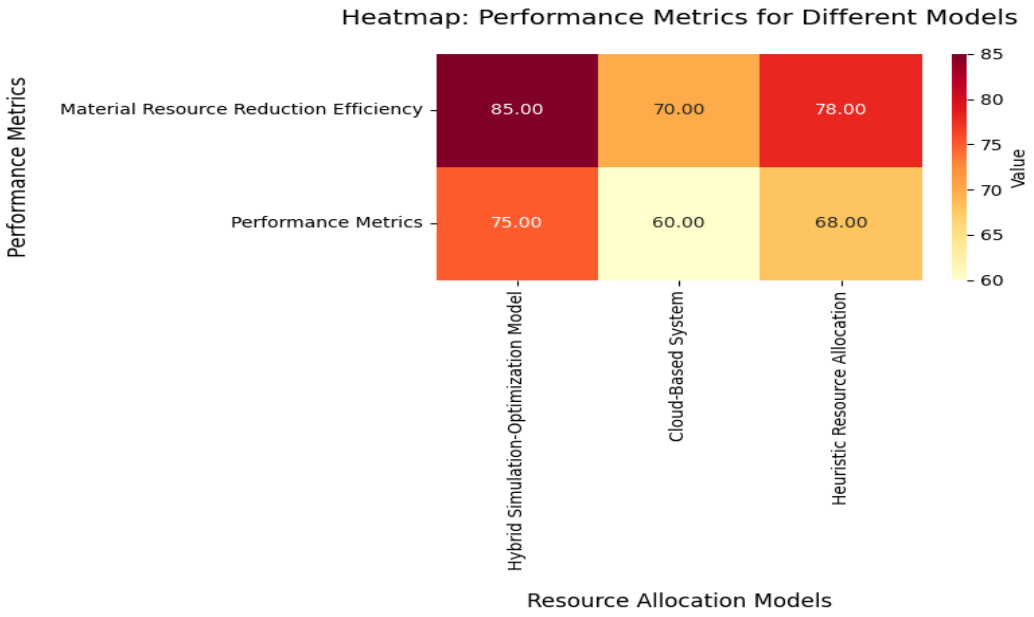



**Fig. 2: Heatmap Comparison of Performance Metrics for Different Models**

Fig. 2 displays the performance measure of Waste Reduction Efficiency and Material Reuse Rate in three models, Hybrid Simulation-Optimization Model, Cloud-Based System and Heuristic Resource Allocation, are provided in Fig 2. The heatmaps have varying color schemes (YlGnBu, Viridis, and Plasma) to contrast the performance of each model on the most crucial indicators. The Hybrid Simulation-Optimization Model performs the best regularly, as the figures provide 85 % waste reduction and 75 % material reutilization, which means that it is better at optimizing the technologies of the circular economy.

## Conclusion

The paper has given a roadmap of the circular economy technologies in manufacturing sectors, and specifically recycling, re-manufacturing, reuse and waste reduction through closed-loop manufacturing. The study has come up with an elaborate Hybrid Simulation-Optimization Model to compare and rank these technologies and found the effectiveness in eliminating waste, increasing material reuse, and making recycling more efficient. The Full Model (MCDA + GIS + All Criteria) showed the most successful results in the waste elimination, resource use, and social Acceptance. The model allowed monitoring waste in real-time and enhancing the overall processes of the circular economy by introducing digital technologies, such as IoT and blockchain-based traceability. Statistically, it was determined that the Hybrid Simulation-Optimization Model possessed waste reduction efficiency of 85 %, material reuse of 75 % and recycling efficiency of 80 %; thus, being superior to other models. The findings highlight the need to combine the multi-criteria decision analysis (MCDA) and Geographic Information Systems (GIS) to thoroughly evaluate the circular economy technologies. The orientation of the paper also focused on social Acceptance as a driver of the uptake of the circular practices, an essential measure of the long-term sustainability. The MCDA based road mapping approach offers a methodological way of assessing circular economy technologies in manufacturing. Further studies on the incorporation of modern digital solutions and industry-specific solutions to make further improvements in the sustainability of circular economy practices are recommended. Moreover, further research on how this strategy can be applied to other industries and regions should provide more information on how to overcome the obstacles to its implementation and promote the prevalence of technologies based on a circular economy.

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