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Towards sustainable manufacturing: A comprehensive analysis of circular economy key performance indicators in the manufacturing industry

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Abstract

In the pursuit of sustainable development, the concept of Circular Economy (CE) has emerged as a transformative alternative to the traditional linear economic model characterized by take, make, use, and dispose practices. However, there is a growing recognition of the limitations of the linear economy in addressing contemporary global challenges, leading to a pressing need for a more regenerative approach. This study aims to explore and analyze Key Performance Indicators (KPIs) associated with the circular economy, particularly focusing on the manufacturing industry, to provide a valuable guide for enterprises looking to integrate CE principles effectively and reinforce sustainability. The novelty of this study lies in its comprehensive examination of KPIs that embrace sustainability's triple bottom lines - environmental, economic, and social dimensions. The systematic selection of relevant KPIs and the utilization of Social Network Analysis (SNA) to identify the most influential CE KPIs within the manufacturing industry add depth to the research. By identifying and upgrading significant KPIs representing various facets of CE development, this study contributes to a more meticulous understanding of how enterprises can measure their progress towards circularity. In each of the triple bottom lines of sustainability, five significant KPIs were recognized and upgraded to the second assessment process, where these 15 KPIs are analyzed using SNA to obtain 5 aggregated KPIs. The comprehensive analysis of the obtained fifteen KPIs culminates in aggregated CE indicators, primarily strategies and initiatives (SI), material efficiency (ME), productivity of remanufacturing (OR), technology investment (ROR), and eco-innovation (EI). The aggregated Key Performance Indicators (KPIs) displayed an extreme value of the weighted average index attributed to strategies and initiatives KPI with a value of 0.067. These aggregated KPIs provide a practical framework for manufacturers to assess and optimize their circular economy practices. It's essential to note that all binary values incorporated in the proposed approach are derived from an extensive literature review. These values may vary depending on the specific objectives of individual manufacturing firms or focus groups. As a result, the proposed approach is adaptable to diverse manufacturing industries, allowing customization to suit the unique input criteria of each firm or group. Significantly, the current work emphasizes the influential role of manufacturers in shaping a sustainable future in alignment with development goals.

Introduction

In terms of economic models, the linear economy model has dominated the world of economics for centuries, propelling societies towards extraordinary growth and prosperity. Although this model has contributed to economic growth, it faces increasing challenges in the modern era. This seemingly unassailable model accompanies hidden perils that threaten

to undermine the planet's ecological stability and the well-being of future generations. In this traditional model, resources are extracted, transformed into products, used by consumers, and ultimately discarded as waste. Consequently, the adoption of a linear economy model results in environmental impacts, health problems, source scarcity, economic issues, and price volatility of products [1]. These challenges highlight the pressing demand for a shift towards sustainability by utilizing a new model that overcomes the previously mentioned limitations. In light of the shortcomings of the linear economy model, several initiatives were performed to modify the linear economy model and convert it into a closed-loop material flow [2,3].

Governments, industries, and societies around the world initiated several activities including recycling, reduction, and remanufacturing which were traced to the times of the Second World War in automotive industries during the 1940s [4]. These initiatives were the spark that ignited the concept of the Circular Economy (CE). The circular economy has various possibilities to be defined according to eco-industrial development [5], 6R principles (i.e., Reduce, Reuse, Recycle, Recover, Remanufacture, and Redesign) [6], and economic aspects [7]. By design and intention, Circular Economy (CE) strives to achieve an industrial economy that is both environmentally and economically regenerative [8]. Consequently, the implementation of CE practices based on the concept of 6R principles has proven the endurance of the worldwide to cope with global challenges.

A worldwide investigation is ongoing to identify the essential requirements for gradually integrating the new model into diverse business sectors [9]. This integration aims to assist industries in achieving the United Nations' sustainable development goals. However, for the successful transition to CE model in the manufacturing sector, a specific set of Key Performance Indicators (KPIs) should be established and defined to capture the change in the system's attributes. These KPIs vary according to the systems' objectives and requirements along with the different preferences of manufacturers and stakeholders. Various efforts have been made in the open literature to provide innovative solutions for implementing the CE model, coupled with the judicious selection of KPIs which will be discussed in the following sections.

While numerous initiatives have been undertaken worldwide to promote CE practices, there remains a need for a systematic approach to implement and assess the transition to a circular economy, especially in the manufacturing sector. This approach should satisfy the demand to minimize the environmental impacts, encourage the regenerative use of resources, and increase the profitability of companies. Through the performed extensive literature review, most of the indicators that are published in the open literature failed to

capture different aspects and stages of the circular economy. This paper addresses the inadequacies of existing frameworks in the open literature related to the implementation and assessment methodology of the Circular Economy (CE). By filling these research gaps, this paper becomes a crucial contributor to strengthening the role of manufacturers and stakeholders in making efficient decisions and developing technological capabilities essential for achieving sustainable development goals. Its novelty lies in its ability to support the manufacturing industry in developing and determining technological capabilities essential for achieving sustainable development goals and shaping a better future. Furthermore, this study offers a novel guideline that aligns with the outlines of the 28th meeting of the Conference of the Parties (COP 28) held in December 2023 in Expo City, Dubai, UAE [10].

This paper examines several critical research questions to enhance sustainability and promote circular economy principles in the manufacturing sector:

1. How can existing circular economy frameworks be enhanced and optimized to improve decision-making in the manufacturing sector?

2. Which Key Performance Indicators (KPIs) are essential for promoting sustainability in manufacturing while aligning with circular economy principles across economic, environmental, and social dimensions?

3. What is the process for developing a guideline that is comprehensive and balanced to steer sustainability efforts in the manufacturing industry?

4. Which analytical methodologies can be applied to thoroughly evaluate and optimize these identified KPIs, leading to better environmental and economic outcomes?

By addressing these questions, this paper aims to empower manufacturing stakeholders, advance sustainable development objectives, and align with international initiatives to mitigate climate change. The ultimate goal is to support environmentally responsible and circular practices within the manufacturing sector.

Therefore, this work serves as a valuable guideline and resource for the manufacturing industry, providing insights into Key Performance Indicators (KPIs) for the circular economy. These KPIs were meticulously selected through an extensive literature review, and the relationships between each pair of KPIs were thoroughly discussed. By utilizing Social Network Analysis (SNA) and measures of centrality, the most influential circular economy KPIs were identified. Based on the findings, this study provides recommendations to optimize these significant KPIs for the manufacturing industry. By adopting the proposed

systematic approach in this paper, governments, stakeholders, and manufacturers can enhance the circularity of materials in their applications, contributing to a more sustainable and environmentally friendly manufacturing process, and promoting circular economy practices.

To achieve the research objectives, the paper is structured as follows: Section 2 outlines the conducted literature review and research gaps. Section 3 presents the proposed research methodology in a flowchart and the KPIs selection process, categorizing them by environmental, economic, and social aspects and distinguishing them as quantitative or qualitative. Section 4 introduces the Social Network Analysis (SNA) and its contribution to the proposed approach. Section 5 delves into scenarios utilizing Social Network Analysis (SNA) outcomes, illustrated through examples showcasing interrelationships between pairs of Key Performance Indicators (KPIs). Section 6 details the proposed assessment technique and showcases the aggregated KPIs. Additionally, Section 7 discusses the aggregated indicators and provides industrial recommendations for each KPI. Finally, in Section 8, conclusions and suggestions for future research are presented.

Section snippets

Literature review

The Circular Economy (CE) model has demonstrated its ability to revolutionize the future of manufacturing industries. This model offers several advantages to the manufacturing sector by enhancing the relationship between society and industry through promoting collaboration among all supply chain participants [11]. The integration of sustainable practices in manufacturing industries reduces input costs, minimizes waste, and boosts the profitability of CE practices. Additionally, the adoption of…

The proposed assessment and research methodology

In the light of the inadequacies of the existing CE frameworks, this paper proposes a research methodology that focuses on the proper selection of KPIs. To better understand the methodology employed in this research work (see Fig. 1), which illustrates the work flowchart. A comprehensive literature review, using reputable publishing houses, was conducted to identify relevant KPIs, followed by a rigorous categorization and refinement process for the KPIs that eliminates redundancy, or…

Social network analysis in circular economy

This section sheds light on the crucial concepts and tool used in the current study to determine the interconnections between the selected Key Performance Indicators (KPIs) in Section 3.1. Specifically, it presents the concept of Social Network Analysis (SNA) as a pivotal tool in this study, alongside its relevance to the proposed Circular Economy (CE) model. Additionally, the chapter explores the concepts of three centrality measures: degree centrality, betweenness centrality, and closeness…

Interconnections and relationships of CE indicators: adjacency matrices

This section showcases selected examples of the investigated relationships among Key Performance Indicators (KPIs) in the context of circular economy practices within the manufacturing industry. The study analyzes adjacency matrices, as a foundation to SNA, to examine correlations and efficiency, focusing on sustainability's triple bottom lines. These relationships shed light on the effectiveness and efficiency of circular economy practices within the manufacturing industry. It emphasizes the…

Results and analysis

This section presents findings and analysis, using social network analysis to obtain statistical centrality measures. Interpretation of key features associated with each centrality measure is provided, and normalized centrality measures are utilized to assess the significance of individual KPIs. Significant KPIs from each matrix are compiled in an adjacency matrix, discussing interconnections between each pair of KPIs. Social Network Analysis is employed to obtain centrality measures for…

Discussion and recommendations: aggregated CE key performance indicators

This section focuses on the contribution of the top five KPIs, as highlighted in Fig. 15, to the development of the circular economy. The research equips manufacturers, policymakers, and stakeholders with tools to monitor, set targets, make informed decisions, and implement strategies for fostering sustainable development within the CE model. Furthermore, this section examines the relationship between the Sustainable Development Goals (SDGs) and the implementation of Circular Economy (CE)…

Conclusions and future work

In conclusion, this study has conducted a thorough investigation and analysis of Circular Economy (CE) indicators in the manufacturing industry, resulting in the development of a comprehensive model. The proposed model in the current study serves as a tool that signifies the manufacturers' role in the decision-making process and comprehensively captures sustainability's triple bottom lines. Throughout this study, CE Key Performance Indicators (KPIs) were precisely collected and analyzed using a …

CRediT authorship contribution statement

Dina Aljamal: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Amr Salem:** Writing – review & editing, Validation, Investigation, Formal analysis. **Navneet Khanna:** Writing – review & editing, Visualization, Software, Methodology. **Hussien Hegab:** Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing.…

Declaration of competing interest

The authors declare and confirm no conflict of interest concerning the submitted manuscript. No funding or grants were received for the study.…

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