14th Annual International Conference on Industrial Engineering and Operations Management Dubai United Arab Emirates (UAE), February 12-14, 2024

Publisher: IEOM Society International, USA DOI: 10.46254/AN14.20240488
Published: February 12, 2024

Circular Economy in Manufacturing: Maximizing Resource Efficiency and Minimizing Waste

Onu Peter and Charles Mbohwa
Department of Quality and Operations Management
Faculty of Engineering and the Built Environment, University of Johannesburg, P. O. Box 524, Johannesburg, South Africa.
onup@uj.ac.za

Abstract

The circular economy promotes a closed-loop system where resources are used for as long as possible and challenges the conventional linear model of "take-make-dispose." In the manufacturing industry, this entails creating products and procedures that can be recycled, repaired, or reused to reduce the use of virgin materials and environmental impact. However, understanding the implementation barriers is crucial before investing in a strategic approach for adoption. This study analyzed challenges using the index of the Item Objective Congruence (IOC) technique and expert opinions. The findings identified seven significant challenges: Lack of Awareness and Education, Modifications in Consumer Behavior, Infrastructure Limitations, Lack of Skills and Technical Challenges, Lack of Government Support, Environmental Impact, and Lack of Guidelines and Standards, which play significant roles in the successful implementation of circular economy practices in the manufacturing industry. These findings provide valuable guidance for the strategic implementation of circular economy principles in manufacturing and practical insights and recommendations to businesses, policymakers, and stakeholders on effectively embracing circular economy principles in the manufacturing industry.

Keywords
Circular economy, Manufacturing, Waste, Resources maximization, Implementation strategies

1. Introduction
The manufacturing industry plays a critical role in global economic growth and development (Peter & Mbohwa, 2019). However, its current linear model of production and consumption, known as the "take-make-dispose" approach, has led to resource depletion and environmental degradation (Bjørnbet et al., 2021). This model relies heavily on extracting finite resources, resulting in significant waste generation and greenhouse gas emissions (Ulian et al., 2020). To address these issues, the circular economy concept has gained prominence, offering a paradigm shift towards a closed-loop system that maximizes resource efficiency and minimizes waste (Bjørnbet et al., 2021). The circular economy is a regenerative approach that challenges the linear model by emphasizing value retention in products, materials, and resources for as long as possible (Bjørnbet et al., 2021). It advocates for transforming the manufacturing industry into a system that operates in cycles, where waste is minimized and resources are continuously reused, recycled, or remanufactured (Koszewska, 2018). By transitioning to a circular model, the manufacturing sector can reduce its reliance on virgin materials and mitigate environmental impacts associated with waste generation, such as pollution and carbon emissions (Badhotiya et al., 2022; Sousa-Zomer et al., 2018).

This study explores the principles and advantages of the circular economy within the manufacturing context by analyzing recent developments and trends in the literature. This study delves into case studies of manufacturing businesses that have successfully applied circular economy principles and assessed the positive effects on their financial performance and the environment. Furthermore, through expert interviews, this study identifies the challenges and potential barriers to implementing circular economy principles in manufacturing. Our objective is to provide a comprehensive understanding of the effective implementation strategies for circular economy practices in the manufacturing sector. Ultimately, this research will provide valuable insights and recommendations to businesses, policymakers, and stakeholders on effectively embracing circular economy principles in the manufacturing industry.

2. State of the Art

2.1 Circular Economy Principles in Manufacturing

The manufacturing industry plays a significant role in resource depletion, waste generation, and environmental pollution (Peter Onu & Mbohwa, 2021a; Peter & Mbohwa, 2019). Adopting circular economy principles has emerged as a promising approach to address these challenges. Circular economy principles in manufacturing encompass several key aspects: design for durability and repairability, recycling and material recovery, and remanufacturing and reuse (Jawahir & Bradley, 2016). Design for durability and repairability focuses on designing products with longevity in mind, utilizing high-quality materials and incorporating modular components for easy repair (Mesa et al., 2022). The recycling and material recovery principle emphasizes implementing efficient sorting and separation processes, advanced recycling technologies, and robust material recovery systems (Domenech & Borrion, 2022). Remanufacturing and reuse involve refurbishing and repairing used products to a like-new condition, extending their lifespan and reducing the demand for new manufacturing (Russell & Nasr, 2023). These principle aims to promote resource conservation, reduce waste, and extend the lifespan of products, thereby minimizing the need for frequent replacements. By reintroducing valuable resources into the manufacturing process, this principle contributes to a more sustainable manufacturing ecosystem and reduces resource depletion. In addition, it aids in waste reduction and optimization of resources by identifying new applications and facilitating the repurposing of products.

In contrast to the traditional linear model of "take-make-dispose," the circular economy represents a fundamental shift. The linear model is inherently wasteful and unsustainable, leading to resource depletion, environmental degradation, and waste accumulation (Ulian et al., 2020). In contrast, the circular economy replaces this linear flow with a closed-loop system, utilizing resources for as long as possible. Adopting circular economy principles is crucial for several reasons. Firstly, it enables resource conservation by reducing reliance on virgin materials and minimizing the extraction of limited resources, ensuring their availability for future generations. Secondly, circular economy practices significantly reduce waste generation and its associated environmental impacts, such as pollution and carbon emissions (Dhonde & Patel, 2020; Hettiarachchi et al., 2022).

Moreover, embracing circular economy principles can lead to cost savings and enhanced competitiveness for manufacturers (Hettiarachchi et al., 2022). Also, optimizing resource utilization, minimizing waste, and embracing innovative practices, can lead to companies lowering production costs, improve operational efficiency, and gain a competitive edge in the market. Lastly, adopting circular economy principles enhances business resilience and longevity (Kennedy & Linnenluecke, 2022). By embracing sustainability, manufacturers can adapt to changing consumer demands, regulatory requirements, and market dynamics, ensuring long-term viability.

2.2 Recent Developments and Trends in Circular Economy

Advancements and Innovations in Circular Economy in Manufacturing

Researchers and manufacturers have made strides in material innovation, focusing on developing sustainable materials conducive to circularity (Bocken & Konietzko, 2022). This includes exploring bio-based and biodegradable materials, recyclable polymers, and innovative composite materials with improved recyclability and durability. Such advancements open up new possibilities for designing more environmentally friendly products that can be effectively incorporated into the circular economy framework (Mesa et al., 2022). Integrating digital technologies and data analytics has also played a vital role in optimizing circular economy practices in manufacturing. By utilizing smart sensors, Internet of Things (IoT) devices, and advanced data analytics platforms, manufacturers can monitor production processes in real time, predict maintenance needs, and optimize resource utilization (Hennemann Hilario da Silva & Sehnem, 2022). These digital technologies enhance the efficiency and effectiveness of circular economy implementation, ensuring that resources are used optimally (Bag et al., 2022). Collaborative networks and innovative business models have emerged as significant drivers of circular economy adoption. Sharing platforms, such as peer-to-peer rentals and product-as-a-service models, facilitate extended product use and minimize the need for ownership. This shift in mindset promotes resource efficiency and reduces waste by encouraging product utilization rather than ownership, thereby fostering a more circular economy (Bjørnbet et al., 2021; Gamidullaeva et al., 2022; Mesa et al., 2022).

Implications of Circular Economy Principles in Manufacturing

Examining successful case provides valuable insights into the practical application of circular economy principles in manufacturing. Interface Inc., a global flooring manufacturer, has exemplified this through its "Mission Zero" approach (Khoo, 2018). Through this program, Interface has implemented innovative design strategies, sustainable material sourcing practices, and closed-loop manufacturing processes that allow the recovery and recycling of used products. This has resulted in successfully recycling millions of pounds of discarded carpet tiles, preventing them from ending up in landfills and reducing the need for virgin materials.

Another noteworthy example is Philips, a leading electronics company, which has embraced circular economy principles by transitioning from selling lighting products to providing lighting as a service (Fleming & Zils, 2014; Signify, 2015). By retaining ownership of the lighting systems and offering maintenance and upgrades, Philips ensures maximum product lifespan and value extraction. This innovative business model has allowed them to optimize resource utilization, reduce waste, and create additional revenue streams (Pedersen & Clausen, 2018). By offering lighting as a service, Philips is able to provide high-quality lighting solutions to customers while retaining control over the products, enabling them to ensure that the systems are used efficiently and effectively throughout their lifespan (Signify, 2015). This approach represents a successful example of how companies can incorporate circular economy principles into their operations to achieve environmental and business benefits.

3. Methodology

This section provides an overview of the data collected and utilized to fulfill the research objectives. The research approach employed for article selection and analysis is the Systematic Literature Network Analysis (SLNA) (Peter Onu et al., 2023b). Various reputable databases, including Web of Science, Google Scholar, and Scopus, were considered for the literature analysis from 2013 to 2023. Among the initial pool of *29* articles that focused on challenges and potential barriers to implementing circular economy principles in manufacturing, ten were identified as irrelevant based on their title, and eight did not align with the research objectives, leaving 11 papers in the review. After identifying the 11 potential barriers through reviewing relevant literature, it is still necessary to validate them to ensure they are significant for implementing circular economy practices in the manufacturing sector. The validation was based on the interviews of seven specialists who have experience and knowledge in circular economy principles by using the index of item-objective congruence (IOC) approach. Item Objective Congruence Analysis is a procedure used in test development to assess content validity and evaluate how well each test item measures the construct it was designed to measure (Turner & Carlson, 2003). The IOC method evaluates the match between items and objectives, which is the most critical assessment during the content validation stage (Turner & Carlson, 2003) to foster the implementation potential and represent the quantitative data perspective.

A group of experts with diverse backgrounds and extensive knowledge of circular economy practices in manufacturing were consulted for their insights. The expert panel included a sustainability consultant, a behavioral economist, an infrastructure specialist, a technical expert, and a policy analyst. A university lecturer who has published several articles on circular economy practices in manufacturing was also consulted. Three experts in the panel serve as managers in renowned sustainable manufacturing-inclined companies, while one expert serves as a director. The expert panel's combined expertise and experience provide a comprehensive understanding of circular economy practices in manufacturing, ensuring that the insights gained are rigorous and thorough. The extent to which the tool measures what is intended to be evaluated is content validity, which is the most significant validity. Expert judgment is the practical method for determining the content truth. At least five specialists should evaluate each item to determine whether each barrier truly supports consistency of implementation in circular economy principles in manufacturing. The Item-Objective Congruence (IOC) method involves a two-phase process for evaluating barriers to implementing circular economy practices in manufacturing.

In the first phase, each barrier is evaluated by an expert who assigns a score of either 1, -1, or 0 based on their level of certainty regarding the barrier's relevance to circular economy implementation practices in manufacturing. If the expert is certain that the barrier is relevant, they assign a score of 1. Conversely, if the expert is certain that the barrier is not relevant, they assign a score of -1. If the expert is uncertain about the barrier's relevance, then they assign a score of 0. In the second phase, the scores assigned by the experts are averaged to generate an IOC index for each obstacle. Barrier scores with an IOC index below 0.5 are deemed unfit and should be removed from the list. Scores between 0.5 and 1.0 indicate significant barriers that require further consideration to implement circular economy practices in manufacturing.

4. Results and Analysis

4.1 Challenges Towards Implementing Circular Economy in Manufacturing

Implementing circular economy principles in the manufacturing sector is not without its challenges. Overcoming these barriers requires careful consideration and strategic approaches. According to the review of 11 published articles that focused on investigating the challenges and barriers to implementing circular economy principles in the manufacturing sector (Agyemang et al., 2019; Ayçin & Kayapinar Kaya, 2021a; Badhotiya et al., 2022; Bag et al., 2022; Bjørnbet et al., 2021; Chhimwal et al., 2022; Hettiarachchi et al., 2022; Peter Onu et al., 2023a; Priyadarshini et al., 2022; Sousa-Zomer et al., 2018; Wilson, 2015), 11 potentials.

Mindset and Cultural Shift (C1): Shifting from a linear model to a circular economy necessitates a significant mindset and cultural shift within manufacturing organizations. It involves reevaluating traditional approaches, embracing new paradigms, and cultivating a culture of innovation and sustainability throughout the organization (Chhimwal et al., 2022; Hettiarachchi et al., 2022).

Lack of Awareness and Education (C2): Many manufacturers may have limited awareness and understanding of circular economy principles, their benefits, and implementation strategies. To address this, comprehensive education and knowledge dissemination efforts are crucial to facilitate adopting and integrating circular economy practices (Ayçin & Kayapinar Kaya, 2021b; Elf et al., 2022).

Complex Supply Chains (C3): Manufacturing supply chains are often intricate and globally dispersed, posing challenges in tracking, and managing materials and products throughout their life cycles. The lack of transparency and traceability within supply chains presents a barrier to the effective implementation of circular economy practices (Bjørnbet et al., 2021; Chhimwal et al., 2022; Hettiarachchi et al., 2022; Priyadarshini et al., 2022).

Need for New Business Models (C4): Embracing circular economy principles often requires a shift from traditional linear business models to innovative circular business models. This transition may involve significant investments, changes in operational processes, and collaboration with stakeholders across the value chain (Wilson, 2015).

Modifications in Consumer Behaviour (C5): Successful implementation of circular economy principles relies on consumers' willingness to adopt sustainable consumption patterns, such as sharing, renting, or purchasing products with longer lifespans. Encouraging behavioural changes and promoting a shift towards more sustainable consumer choices can be a significant challenge (Ayçin & Kayapinar Kaya, 2021b; Elf et al., 2022; Farrell et al., 2020).

Infrastructure Limitations (C6): Insufficient infrastructure for recycling, reusing, and remanufacturing can impede the implementation of circular economy practices in manufacturing. The lack of adequate collection systems, sorting facilities, and recycling capabilities hinder the efficient recovery and reintroduction of materials into the manufacturing process (Bjørnbet et al., 2021; Chhimwal et al., 2022; Hettiarachchi et al., 2022; Peter Onu & Mbohwa, 2021b; Priyadarshini et al., 2022).

Lack of Skills and Technical Challenges (C7): Addressing the technical challenges of circular economy implementation is essential. This includes ensuring access to relevant high-tech knowledge, technical expertise, worker competency, and IT skills. Additionally, the complexity of certain technologies, such as 3D printers, requires careful consideration of their implementation and management (Bjørnbet et al., 2021; Chhimwal et al., 2022; Hettiarachchi et al., 2022; Peter Onu & Mbohwa, 2021b).

Lack of Government Support (C8): Insufficient government support can hinder the development and evaluation of critical aspects of circular economy adoption. Adequate government policies, regulatory standards, and support are necessary to create an enabling environment for circular economy practices (Bjørnbet et al., 2021; Chhimwal et al., 2022; Hettiarachchi et al., 2022; Priyadarshini et al., 2022).

Environmental Impact (C9): Adopting certain technologies, like cloud computing and blockchain, among other emerging techniques, can increase electricity and energy consumption, resulting in higher carbon emissions. It is important to consider and mitigate these environmental effects in the pursuit of circular economy goals (Et al., 2021, Hettiarachchi et al., 2022).
Issues with Collaboration and Network Establishment (C10): Lack of collaboration, agreement, and coordination within an organization and among supply chain partners can impede the acceptance and implementation of circular economy practices. Establishing solid collaborative networks and fostering partnerships is essential for success (Chhimwal et al., 2022; Peter et al., 2023b).

Lack of Guidelines and Standards (C11): The lack of operational guidelines, industry standards, suitable indicators, techniques, and approaches for implementing a circular economy poses a challenge. Addressing this issue requires the development of standardized frameworks and best practices to implement circular economy initiatives in manufacturing (Hettiarachchi et al., 2022; Priyadarshini et al., 2022).

According to the analysis presented in Table 1, it is evident that several challenges, including Mindset and Cultural Shift (C1), Collaboration and Network Establishment (C10), Complex Supply Chains (C3), and the Need for New Business Models (C4), have been eliminated from the list of barriers related to implementing circular economy practices in manufacturing. The IOC (Index of Coincidence) values for these challenges are below 0.5, indicating that they do not significantly impact the adoption and implementation of circular economy principles in the manufacturing sector. These findings suggest that these specific challenges, although relevant in other contexts, may not be primary obstacles to implementing circular economy practices in manufacturing. While the mindset and cultural shift, collaboration, complex supply chains, and new business models are undoubtedly important, their influence may not be as significant regarding circular economy adoption in the manufacturing sector (Table 2).

Table 3. Index of the IOC

Challenges	**IOC index**
Mindset and Cultural Shift (C1)	-0.57
Lack of Awareness and Education (C2)	0.78
Complex Supply Chains (C3):	0.45
Need for New Business Models (C4):	-0.25
Modifications in Consumer Behavior (C5):	0.59
Infrastructure Limitations (C6):	0.78
Lack of Skills and Technical Challenges (C7):	0.88
Lack of Government Support (C8):	0.88
Environmental Impact (C9):	0.63
Issues with Collaboration and Network Establishment (C10):	-0.38
Lack of Guidelines and Standards (C11):	0.88

This analysis highlights the need to focus on other challenges with higher IOC values more directly linked to implementing circular economy principles. By prioritizing these specific challenges, manufacturers can allocate their resources and efforts more effectively to overcome the barriers that substantially impact the successful embracing of circular economy practices in the manufacturing industry. The challenges with higher IOC values, namely Lack of Awareness and Education (C2), Modifications in Consumer Behaviour (C5), Infrastructure Limitations (C6), Lack of Skills and Technical Challenges (C7), Lack of Government Support (C8), Environmental Impact (C9), and Lack of Guidelines and Standards (C11), play significant roles in the successful implementation of circular economy practices in the manufacturing industry. These insights were corroborated through interviews with five experts in the field.

Expert 1, a sustainability consultant, emphasized raising awareness and educating manufacturers about circular economy principles. Lack of awareness and understanding of the benefits and strategies of circular economy practices can hinder adoption. Comprehensive educational programs and knowledge-sharing initiatives must be developed and implemented throughout the manufacturing sector to overcome this.

Expert 2, a behavioural economist, highlighted the pivotal role of consumer behaviour in driving the adoption of circular economy practices. Shifting consumer preferences towards sustainable consumption patterns, such as sharing, renting, and choosing longer-lasting products, is crucial. Effective communication and targeted campaigns are essential to motivate and empower consumers to make sustainable choices, thus creating demand for circular products and services.

Expert 3, an infrastructure specialist, emphasized the significance of addressing infrastructure limitations. Insufficient collection systems, sorting facilities, and recycling capabilities pose challenges to efficiently recovering and reintroducing materials into the manufacturing process. Collaborative efforts among manufacturers, governments, and waste management entities are necessary to invest in and develop a robust infrastructure to support circular economy practices.

Expert 4, a technical expert, discussed the challenges related to skills and technical aspects of circular economy implementation. The lack of relevant high-tech knowledge, technical expertise, and IT skills can hinder the adoption of innovative practices and technologies. Training programs and skill development initiatives should be implemented to enhance the technical capabilities of manufacturing personnel and enable the successful integration of circular economy principles.

Expert 5, a policy analyst, highlighted the importance of government support in driving circular economy adoption. Insufficient government policies, regulatory frameworks, and financial incentives can hinder the scaling up of circular economy practices. Strong government commitment, including the development of supportive policies, collaboration with stakeholders, and providing financial incentives, is crucial to create an enabling environment for circular economy implementation.

The environmental impact of manufacturing processes, as discussed by all the experts, was seen as a significant challenge. Adopting circular economy practices can help mitigate the environmental impact by reducing waste generation, conserving resources, and lowering carbon emissions. Circular economy strategies such as recycling, reusing, and remanufacturing can contribute to sustainable production and reduce the ecological footprint of the manufacturing industry. The experts also recognized the lack of guidelines and standards as a barrier. Without clear operational guidelines, industry standards, and suitable indicators for measuring circular economy performance can impede implementation. Developing comprehensive guidelines, frameworks, and industry standards is essential to provide manufacturers with a roadmap for effectively adopting and measuring circular economy practices. Thus, these expert insights underline the significance of addressing challenges related to awareness and education, consumer behaviour, infrastructure limitations, skills, technical aspects, government support, environmental impact, and guidelines and standards to implement circular economy practices in the manufacturing industry successfully.

4.2 Insight and Outlook

The challenges and barriers discussed above can significantly impact the feasibility and scalability of adopting circular economy principles in manufacturing. Successfully overcoming these challenges requires a commitment to collaboration, investment, and engagement from stakeholders throughout the value chain. Manufacturers must carefully assess circular practices' economic, operational, and technological feasibility to ensure their successful implementation. Feasibility is a crucial consideration when adopting circular economy principles. Manufacturers must evaluate the viability of circular practices, considering factors such as cost-effectiveness, resource availability, and technological readiness. Scalability is another important aspect to consider. While individual companies may successfully implement circular practices, scaling them up across the manufacturing sector requires coordinated efforts, supportive policies, and robust infrastructure. Resource availability, technological capabilities, and regulatory frameworks play a pivotal role in determining the scalability of circular economy practices, towards widespread adoption and integration of circular principles.

4.3 Implementation Strategies for Circular Economy Practices in the Manufacturing Sector

A comprehensive and holistic approach is crucial to develop effective implementation strategies for circular economy practices in the manufacturing sector. Manufacturers should consider the entire product life cycle and identify opportunities for circularity at every stage. This includes product design, material sourcing, production methods, and post-consumer waste management. By embracing a holistic approach, manufacturers can ensure that circular economy principles are integrated seamlessly throughout their operations.

A key starting point is adopting design for circular economy principles. This involves designing products with durability, reparability, and recyclability in mind. By using modular designs, standardized components, and easily recyclable or biodegradable materials, manufacturers can optimize the potential for reusing, remanufacturing, and recycling.

Enabling efficient material recovery and recycling systems is another critical aspect. Establishing partnerships with recycling facilities, implementing reverse logistics for product take-back, and exploring innovative recycling technologies can ensure that valuable resources are captured and reintroduced into the production cycle.

Collaboration and partnerships play a vital role in successful circular economy implementation. Manufacturers should engage with suppliers, customers, and stakeholders across the value chain to create closed-loop systems. Sharing knowledge, resources, and infrastructure facilitates the exchange of materials, components, and expertise, fostering a circular ecosystem.

Extended Producer Responsibility (EPR) is an essential concept that manufacturers should embrace. Taking responsibility for the entire life cycle of their products, manufacturers should incorporate mechanisms for collecting, reusing, and properly disposing of products at the end of their useful life. EPR regulations and programs incentivize manufacturers to design products with circularity in mind and invest in efficient recovery and recycling systems.

Shifting from a product ownership model to a product-as-a-service model can also drive resource efficiency and circularity. Manufacturers can offer product-as-a-service models where customers pay for the functionality or performance of a product rather than owning it outright. This incentivizes manufacturers to design products for longevity and facilitates their recovery and reuse at the end of the service period.

Investing in technological innovations is essential for effective circular economy implementation. Manufacturers should explore advanced sorting and separation technologies, recycling and remanufacturing processes, and waste-to-energy conversion solutions. Integrating digital technologies like IoT sensors and data analytics can optimize processes, facilitate resource tracking and management, and enable informed decision-making.

Education and stakeholder engagement are critical for raising awareness and driving sustainable practices. Manufacturers should communicate their circular economy initiatives, educate employees, consumers, and other stakeholders about the benefits and principles of circular economy, and encourage consumer participation through educational campaigns and clear communication channels.

Collaborating with policymakers and advocating for supportive policies and regulations is crucial. Manufacturers should work with governments to develop frameworks that incentivize circular economy practices, provide financial support, and establish clear targets for waste reduction, recycling rates, and resource efficiency.

The successful implementation of circular economy principles in manufacturing requires a specific strategic approach that involves several key steps. Manufacturers should start by setting clear and specific goals that align with circular economy principles, such as reducing waste, optimizing resource utilization, and increasing product lifespan. Next, they must assess their current manufacturing processes, evaluating aspects like raw material usage, energy consumption, and product design. This evaluation helps identify areas for improvement. Once these areas are identified, manufacturers can redesign their manufacturing processes, incorporate closed-loop systems, design products for easy disassembly and recycling, and implement material recovery programs (Peter et al., 2023a). The implementation of circular economy principles should span different stages of the product lifecycle, involving sustainable sourcing of raw materials, adopting efficient production processes, and offering repair, maintenance, and upgrade services to extend the product lifespan. Continuous monitoring and evaluation are essential to track progress, identify areas for improvement, and make necessary adjustments. By adopting this strategic approach, manufacturers can minimize their environmental impact, achieve significant cost savings, and explore new revenue streams (Figure 1).

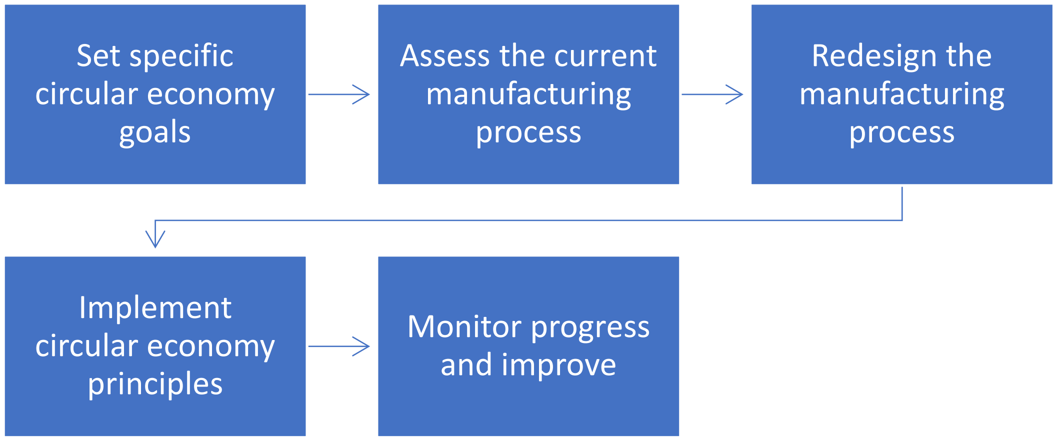

Figure 1. Strategic implementation approach of circular economy principle in manufacturing

Finally, continuous monitoring, measurement, and improvement are vital for successful implementation. Manufacturers should establish metrics and indicators to measure resource efficiency, waste reduction, and the environmental impacts of circular practices.

5. Conclusions

In conclusion, this research underscores the importance of adopting circular economy principles in manufacturing to enhance resource efficiency and minimize waste. A comprehensive understanding of the challenges specific to the manufacturing sector was obtained by reviewing relevant literature and conducting interviews with experts. Seven of the initial lists of 11 barriers were identified as significant based on their average IOC scores exceeding 0.5.

The study's key findings shed light on several insights. Firstly, circular economy principles offer a transformative paradigm for manufacturing, departing from the traditional linear model of production and consumption. These principles encompass designing for durability and repairability, recycling and material recovery, remanufacturing and reuse, and resource efficiency and optimization. Secondly, recent advancements and trends in circular economy practices, such as material innovation, digital technologies, and collaborative networks, demonstrate the potential for improved sustainability and efficiency in manufacturing processes. Lastly, successful case studies of companies like Interface Inc. and Philips illustrate the positive impact of circular economy principles on financial performance, including cost savings and revenue generation, as well as environmental sustainability through waste reduction and resource conservation. Implementing circular economy practices contributes to resource efficiency, waste reduction, and the preservation of natural resources, ultimately fostering a more sustainable and resilient manufacturing industry (Peter Onu et al., 2024c, 2024b, 2024a; Peter Onu et al., 2024b, 2024a; Peter Onu & Mbohwa, 2021c). Manufacturers benefit from long-term cost savings, enhanced competitiveness, and superior environmental performance. Further research should focus on identifying effective implementation strategies and exploring the role of government policies and incentives in supporting circular economy initiatives.

Recommendations are provided for policymakers, businesses, and stakeholders to expedite the transition toward a circular economy in manufacturing. Policymakers are encouraged to sustain the development of regulatory frameworks that facilitate and incentivize circular economy practices, including clear targets, provisions for extended producer responsibility, and eco-design and product standards. Businesses should incorporate circular economy principles into their operations and strategies, investing in research and development, adopting innovative technologies, and collaborating with stakeholders across the value chain. Exploring new business models, such as product-as-a-service and sharing platforms, can also promote resource efficiency and drive changes in consumer behavior. Lastly, stakeholders should foster knowledge sharing and collaboration through industry associations, public-private partnerships, and dialogue platforms, facilitating the exchange of best practices, lessons learned, and success stories.

References

Agyemang, M., Kusi-Sarpong, S., Khan, S. A., Mani, V., Rehman, S. T., & Kusi-Sarpong, H., Drivers and barriers to circular economy implementation. *Management Decision*, 2019, https://doi.org/10.1108/md-11-2018-1178

Ayçin, E., & Kayapinar Kaya, S., Towards the circular economy: Analysis of barriers to implementation of Turkey's zero waste management using the fuzzy DEMATEL method. *Waste Management and Research*, 2021a, https://doi.org/10.1177/0734242X20988781

Ayçin, E., & Kayapinar Kaya, S., Towards the circular economy: Analysis of barriers to implementation of Turkey's zero waste management using the fuzzy DEMATEL method. *Waste Management and Research*, 2021b, https://doi.org/10.1177/0734242X20988781

Badhotiya, G. K., Avikal, S., Soni, G., & Sengar, N., Analyzing barriers for the adoption of circular economy in the manufacturing sector. *International Journal of Productivity and Performance Management*, 2022, https://doi.org/10.1108/IJPPM-01-2021-0021

Bag, S., Sahu, A. K., Kilbourn, P., Pisa, N., Dhamija, P., & Sahu, A. K., Modeling barriers of digital manufacturing in a circular economy for enhancing sustainability. *International Journal of Productivity and Performance Management*, 2022, https://doi.org/10.1108/IJPPM-12-2020-0637

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

Bocken, N., & Konietzko, J., Circular business model innovation in consumer-facing corporations. *Technological Forecasting and Social Change*, 2022, https://doi.org/10.1016/j.techfore.2022.122076

Chhimwal, M., Agrawal, S., & Kumar, G., Challenges in the implementation of circular economy in manufacturing industry. *Journal of Modelling in Management*, 2022, https://doi.org/10.1108/JM2-07-2020-0194

Dhonde, B., & Patel, C. R., Implementing circular economy concepts for sustainable urban freight transport: Case of textile manufacturing supply chain. *Acta Logistica*., 2020, https://doi.org/10.22306/al.v7i2.172

Domenech, T., & Borrion, A., Embedding Circular Economy Principles into Urban Regeneration and Waste Management: Framework and Metrics. *Sustainability (Switzerland)*, 2022, https://doi.org/10.3390/su14031293

Elf, P., Werner, A., & Black, S., Advancing the circular economy through dynamic capabilities and extended customer engagement: Insights from small sustainable fashion enterprises in the UK. *Business Strategy and the Environment*, 2022, https://doi.org/10.1002/bse.2999

Et al., K. K., A Digital Circular Economy for Smart Cities. *Psychology and Education Journal*, 2021, https://doi.org/10.17762/pae.v58i1.925

Farrell, C. C., Osman, A. I., Doherty, R., Saad, M., Zhang, X., Murphy, A., Harrison, J., Vennard, A. S. M., Kumaravel, V., Al-Muhtaseb, A. H., & Rooney, D. W., Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules. I: *Renewable and Sustainable Energy Reviews*, 2020, https://doi.org/10.1016/j.rser.2020.109911

Fleming, T., & Zils, M., Toward a circular economy: Philips CEO Frans van Houten. I: *McKinsey Quarterly*. 2014

Gamidullaeva, L., Shmeleva, N., Tolstykh, T., & Shmatko, A., An Assessment Approach to Circular Business Models within an Industrial Ecosystem for Sustainable Territorial Development. *Sustainability (Switzerland)*, 2022, https://doi.org/10.3390/su14020704

Hennemann Hilario da Silva, T., & Sehnem, S., The circular economy and Industry 4.0: synergies and challenges. *Revista de Gestao*, 2022, https://doi.org/10.1108/REGE-07-2021-0121

Hettiarachchi, B. D., Sudusinghe, J. I., Seuring, S., & Brandenburg, M., Challenges and Opportunities for Implementing Additive Manufacturing Supply Chains in Circular Economy. *IFAC-PapersOnLine*, 2022, https://doi.org/10.1016/j.ifacol.2022.09.545

Jawahir, I. S., & Bradley, R., Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP*, 2016, https://doi.org/10.1016/j.procir.2016.01.067

Kennedy, S., & Linnenluecke, M. K., Circular economy and resilience: A research agenda. *Business Strategy and the Environment*, 2022, https://doi.org/10.1002/bse.3004

Khoo, J., Interface: Net-works - lessons learnt turning nets into carpet. I: *Designing for the Circular Economy*, 2018, https://doi.org/10.4324/9781315113067-30

Koszewska, M., Circular Economy - Challenges for the Textile and Clothing Industry. *Autex Research Journal*, 2018, https://doi.org/10.1515/aut-2018-0023

Mesa, J. A., Gonzalez-Quiroga, A., Aguiar, M. F., & Jugend, D., Linking product design and durability: A review and research agenda. I: *Heliyon*, 2022, https://doi.org/10.1016/j.heliyon.2022.e10734

Onu, P, Pradhan, A., & Mbohwa, C., *EcoMechatronics : Advancing Sustainable Production Through Mechatronic Systems*, 2024a, https://doi.org/10.1109/ieem58616.2023.10406694

Onu, P, Pradhan, A., & Mbohwa, C., *Industry 4. 0 and Beyond: Enabling Digital Transformation and Sustainable Growth in Industry X . 0*, 2024b, https://doi.org/10.1109/ieem58616.2023.10406334
Onu, P, Pradhan, A., & Mbohwa, C., *Sustainable Production Through Competency Development in Smart Manufacturing*, 2024c, https://doi.org/10.1109/ieem58616.2023.10406990
Onu, Peter, & Mbohwa, C., Industry 4.0 opportunities in manufacturing SMEs: Sustainability outlook. *Materials Today: Proceedings*, 2021a, https://doi.org/10.1016/j.matpr.2020.12.095
Onu, Peter, & Mbohwa, C., Nascent technologies in resources conservation and sustainable agricultural development. I: *Agricultural Waste Diversity and Sustainability Issues*, 2021b, https://doi.org/10.1016/b978-0-323-85402-3.00011-5
Onu, Peter, & Mbohwa, C., Reimagining the future: Techno innovation advancement in manufacturing. *Materials Today: Proceedings*, 2021c, https://doi.org/10.1016/j.matpr.2020.12.100
Onu, Peter, Mbohwa, C., & Pradhan, A., *Advancements, Challenges, and Recommendations for Resilient and Decarbonized Future Smart Grids*, 2024a, https://doi.org/10.1109/ICECET58911.2023.10389344
Onu, Peter, Mbohwa, C., & Pradhan, A., *Machine Learning: A Comprehensive Exploration of Fault Detection and Diagnosis in Smart Grids*, 2024b, https://doi.org/10.1109/ICECET58911.2023.10389596
Onu, Peter, Pradhan, A., & Mbohwa, C., Potential to use metaverse for future teaching and learning. *Education and Information Technologies*, 2023a, https://doi.org/10.1007/s10639-023-12167-9
Onu, Peter, Pradhan, A., & Mbohwa, C., The potential of industry 4.0 for renewable energy and materials development – The case of multinational energy companies. *Heliyon*, 2023b, https://doi.org/10.1016/j.heliyon.2023.e20547
Pedersen, S., & Clausen, C., Co-designing For a Circular Economy. I: *Innovation, the Name of the Game in Stockholm*, 2018
Peter, O., & Mbohwa, C., Industrial energy conservation initiative and prospect for sustainable manufacturing. *Procedia Manufacturing*, 2019, https://doi.org/10.1016/j.promfg.2019.05.077
Peter, O., Pradhan, A., & Mbohwa, C., Industry 4.0 concepts within the sub–Saharan African SME manufacturing sector. *Procedia Computer Science*, *217*, 846–855, 2023a, https://doi.org/10.1016/j.procs.2022.12.281
Peter, O., Pradhan, A., & Mbohwa, C., Industrial internet of things (IIoT): opportunities, challenges, and requirements in manufacturing businesses in emerging economies. *Procedia Computer Science*, 2023b, https://doi.org/10.1016/j.procs.2022.12.282
Priyadarshini, J., Kr Singh, R., Mishra, R., & Mustafa Kamal, M., Adoption of additive manufacturing for sustainable operations in the era of circular economy: Self-assessment framework with case illustration. *Computers and Industrial Engineering*, 2022, https://doi.org/10.1016/j.cie.2022.108514
Russell, J. D., & Nasr, N. Z., Value-retained vs. impacts avoided: the differentiated contributions of remanufacturing, refurbishment, repair, and reuse within a circular economy. *Journal of Remanufacturing*, 2023, https://doi.org/10.1007/s13243-022-00119-4
Signify., Philips provides Light as a Service to Schiphol Airport. I: *Signify*, 2015
Sousa-Zomer, T. T., Magalhães, L., Zancul, E., & Cauchick-Miguel, P. A., Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider. *Resources, Conservation and Recycling*, 2018, https://doi.org/10.1016/j.resconrec.2017.10.033
Turner, R. C., & Carlson, L., Indexes of Item-Objective Congruence for Multidimensional Items. *International Journal of Testing*, 2003, https://doi.org/10.1207/s15327574ijt0302_5
Ulian, G., Cojocaru, M., Rusu, E., & Ulian, E., The Role of Sustainable Public Procurements in the Transition Process from the Linear Economy Model To the Circular Economy Model. *Journal of Public Administration, Finance and Law*, 2020
Wilson, L., The sustainable future of the Scottish textiles sector: challenges and opportunities of introducing a circular economy model. *Textiles and Clothing Sustainability*, 2015, https://doi.org/10.1186/s40689-015-0005-y

Biographies

Peter Onu is a professional who is deeply interested in utilizing the Fourth Industrial Revolution to enhance productivity, improve quality assurance and manage risks associated with operations. His primary area of focus is on sustainable digitalization.

Charles Mbohwa is Distinguisehed Professor of Sustainable Engineering and a visiting professor at the University of Johannesburg, South Africa.