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## Towards Circular Supply Chain Excellence: A Conceptual Study on Enablers Using Fuzzy AHP Methodology

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### Abstract:

*Circular supply chains have become essential for sustainably improving the resilience of modern supply chains. Circular supply chains do not follow a linear path as regular supply chains do. Rather, they aim to reuse, recycle, and recover. The research presents a conceptual framework for identifying and prioritizing enablers of circular supply chain excellence through Fuzzy Analytical Hierarchy Process (Fuzzy AHP). Subjecting strategic, technological, operational and collaboration enablers to expert judgments, fuzzy logic was used to address uncertainties and subjective opinions in decision-making. The results show that the most important strategic enablers to achieve CE are leadership commitment and circular vision. Also, the tools of Industry 4.0 improve monitoring, traceability, and data-driven*

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*decisions. The practical implementation of circularity is supported by operational enablers such as reverse logistics and product lifecycle extension and by stakeholder engagement which enhances sustainability outcomes. The study presents both theoretical and practical insights for organizations aiming to achieve excellence in circular supply chain. It also highlights limitations and future research directions related to sector-specific applications and hybridization with advanced decision-making techniques.*

## **Keywords**

*Circular Supply Chain, Fuzzy Analytical Hierarchy Process (Fuzzy AHP), Reverse Logistics, Industry 4.0, Stakeholder Engagement*

## **1. Introduction**

In today's supply chain management, circular supply chains are a major strategy for sustainability and resilience. Circular supply chains are better than the regular linear supply chains because they reuse, recycle and recover to nullify the impact of the project on nature. Reverse logistics is the process that makes circularity possible by returning goods and materials to the supply chain. Reverse logistics barriers and drivers are multi-perspective as mentioned and thereby technological, strategic and operational factors need to be managed in order to achieve excellence in supply chain in a circular way (Govindan & Bouzon, 2018). As shown in below Figure 1, the research process begins with identifying circular supply chain factors, categorizing them, and applying the Fuzzy AHP technique to compute and rank their importance.

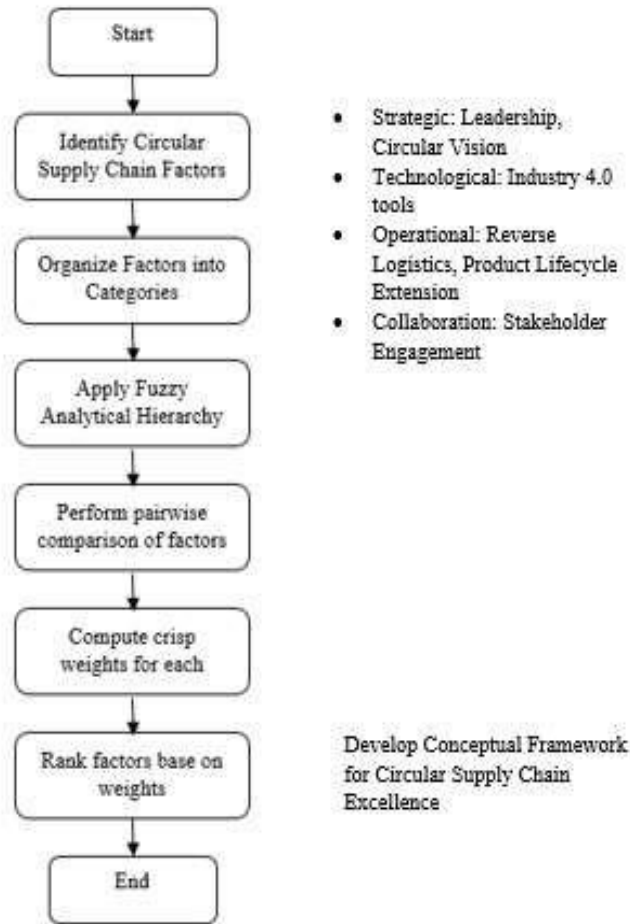


Figure 1: Supply chain management

Source: Own processing using Govindan & Bouzon, 2018

By enhancing flexibility and responsiveness, circular supply chains are enhanced even further by advanced digital technologies. According to Aheleroff et al. (2021), we now enter a new world of Industry 4.0. Mass personalization and real-time monitoring will provide companies with more robust mechanisms to adapt to evolving market and operational conditions. Sustainability or customer centricity, firms today need to adjust quickly to disruptive conditions. The learning of circular economy practices from European multinational enterprises by the author reveals that effective circularity cannot be achieved with the sole use of technology. It requires alignment, engagement with stakeholders, and process innovation (Calzolari, Genovese, & Brint, 2021).

Even with these advancements, there still is a need to systematically identify and prioritize enablers of circular supply chain excellence, especially using structured decision-making methods. With the help of

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the fuzzy analytical hierarchy process (fuzzy AHP) uncertainty in judgments of experts is taken into account in order to prioritize enablers. This will help the practitioners and policymakers. The purpose of this study is to develop a conceptual framework for Circular supply chain enablers and apply Fuzzy AHP methodology to rank them. Which will contribute to both theory and practice.

**1.1 Aim**

To systematically identify, evaluate, and prioritize the critical enablers of circular supply chain excellence using the Fuzzy Analytical Hierarchy Process (Fuzzy AHP), providing actionable insights for both theory and practice.

**1.2 Objectives**

1. To review the existing literature on circular supply chain enablers across strategic, technological, operational, and collaboration dimensions.
2. To develop a conceptual framework for circular supply chain excellence integrating multiperspective enablers.
3. To apply Fuzzy AHP methodology for ranking and prioritizing identified enablers, considering uncertainty in expert judgments.
4. To analyze the relative importance of strategic, technological, operational, and collaboration factors in achieving circularity.
5. To provide practical recommendations for policymakers and supply chain practitioners to enhance circular supply chain performance and sustainability outcomes.

**2. Literature Review**

Name	Year	Aim of Study	Objectives	Scope	Key Findings
Aheleroff et al.	2021	To explore mass personalization as a service in Industry 4.0.	Analyze resilience strategies; Examine digitalization.	Manufacturing & Industry 4.0.	Digital technologies strengthen supply chain resilience and personalization capability.
Zhang et al.	2023	To identify key prospects areas of CSCM adoption	Identifying the factors influencing CSCM adoption	Global supply chain	Major barriers: high cost, cyber security risks, lack of expertise.

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Apaydın & Aladağ	2022	To propose a new DEMATEL threshold identification method.	Develop an improved DEMATEL method; Apply in decision making.	Decision sciences (Hi-Fi audio evaluation).	New method improves accuracy of criteria prioritization in uncertain environments.
Baddley & Rasheed	2023	To analyze AKDN's carbon footprinting approach in healthcare supply chains.	Assess carbon management; Evaluate sustainability practices.	Healthcare sector global.	Accurate carbon measurement boosts green supply chain performance.
Batista, F., & Francisco, L.	2022	To explore critical enablers for circular economy practices in supply chains using a resource-based view	Identify internal and external factors that facilitate CE adoption	Global supply chains	Highlights importance of organizational resources, capabilities, and stakeholder engagement in promoting circular practices. Emphasizes resource-based strategies for circularity.
Beheshti et al.	2023	To study drivers of transition from linear to circular models.	Identify entrepreneurial enablers; Evaluate emerging market conditions.	Emerging nations.	Policy support, innovation, and entrepreneurship are key transition drivers.
Bentahar, Benzidia & Boulakis	2023	To create a taxonomy for green supply chain factors in healthcare.	Classify critical GSCM factors; Develop proactive framework.	Healthcare supply chains.	Leadership, training, and environmental commitment are essential.
Betto & Garengo	2023	To develop a circular pathway for resilience during pandemics.	Identify CE practices that increase resilience; Propose model.	Healthcare systems.	Circularity enhances adaptability and reduces disruption impacts.
Vegter et al.	2023	To review circular supply chain progress in manufacturing.	Assesment of key performance measures	Global manufacturing	Key performance measures associated with CSCM were identified
Bressanelli et al.	2021	To analyze CE enablers in electronic equipment supply chains.	Identify enablers, levers & benefits; Conduct systematic review.	EEE supply chains.	Digital tracking, design for disassembly, and reverse logistics are essential.

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Calzolari, Genovese & Brint	2021	To assess CE practice adoption by European multinational enterprises.	Evaluate adoption levels; Identify drivers & challenges.	European supply chains.	High adoption linked to policy pressure, customer expectations, and internal sustainability vision.
Dastjerdi, Keramati & Keramati	2023	To propose a fuzzy framework for AI-integrated CRM adoption.	Identify adoption factors; Prioritize using hybrid fuzzy MCDM.	Healthcare CRM systems.	Technological readiness and data quality are most influential.
Daú et al.	2019	To propose CE transition framework with CSR mirror for healthcare supply chain 4.0.	Combine CE, CSR, and Industry 4.0 concepts.	Healthcare 4.0.	CE transition requires digital maturity + CSR integration.
Liu et al.	2023	To analyse the closed loop supply chain	Assessing the closed loop supply chain	Global CSCM	Assessed the CSCM network design with flexible capacity
Dohale et al.	2023	To analyze enablers of circular supply chains in Indian apparel.	Use Neutrosophic-ISM; Identify interrelationships.	Indian apparel industry.	Collaboration, government support, and technology are foundational enablers.
Erol et al.	2023	To examine urban-industrial symbiosis in CE.	Explore symbiosis mechanisms; Evaluate operational benefits.	Urban industrial clusters.	Symbiosis boosts material efficiency and reduces resource dependency.
Raja Zuraidah Rasi et al.	2023	To assess current state of art in CSCM domain	Identifying the key challenges faced in CSCM adoption	Global supply chain	Key challenges in CSCM adoption were identified
Fobbe & Hilletoft	2023	To analyze stakeholder engagement in CE manufacturing.	Identify engagement practices; Assess effect on CE adoption.	Manufacturing sector.	Collaboration and stakeholder involvement strongly influence CE success.
Govindan & Bouzon	2018	To develop a multi-perspective framework for reverse logistics	Identify barriers & drivers; Build conceptual framework.	Reverse logistics across industries.	Strategic, economic, and technological barriers are most critical;

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		barriers and drivers.			collaboration enhances RL efficiency.
Kazancoglu, T., Sagnak, E., & Aksoy, S.	2022	To identify critical success factors for circular supply chain management in the food industry	Evaluate factors impacting CE adoption in food supply chains	Food industry	Emphasizes supply chain collaboration, regulatory compliance, process optimization, and innovation. Suggests that integrating these factors improves efficiency and sustainability.
Mangla, S. K., Xu, Y., & Tiwari, R.	2021	To examine barriers to adoption of circular supply chain practices in emerging economies	Identify barriers and challenges in adopting circular supply chain practices	Emerging economies' manufacturing and supply chain sectors	Barriers include lack of awareness, limited technology adoption, financial constraints, and policy gaps. Highlights need for integrated strategies for adoption.
Nair, B., Luthra, S., & Kumar, R.	2022	To analyze enablers of circular supply chain in the manufacturing sector	Develop a structural model for evaluating enablers	Manufacturing sector across industries	Key enablers include leadership commitment, technology integration, stakeholder collaboration, and policy support. Provides prioritization of enablers for effective implementation.
Sharma, R. K., & Dey, A.	2022	To assess enablers of circular economy in Indian manufacturing using ISM approach	Prioritize enablers and understand their interrelationships	Indian manufacturing sector	Structural modeling identifies technological readiness, leadership, policy support, and training as key drivers. Offers insights for strategic planning and operational implementation.

## 2.1 Research gap

There are still many gaps in the literature on circular supply chains. Much of the literature presents a specific focus and study of individual enablers that are either technological, operational or strategic—with little or no integration across the three categories or a comprehensive framework to assess circular supply chain excellence. Most enablers have been recognized. However, there is little use and application of

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multi-criteria decision-making methods like Fuzzy AHP, which rank and weigh systematically. There are few context-specific studies, especially in emerging economies, and the health-care sector lessens within and cross-sector generalizability. In addition, industry 4.0 tools, AI, and IoT as enablers are recognised but not properly quantified in decision-making frameworks. Although stakeholder collaboration and inter-organizational engagement are key, little attention has been paid to them. Most studies don't offer a lot of practical tips on how to do and measure which works. In short, sustainability, economic and social optionality is not sufficiently combined, limiting the holistic understanding of circular supply chain effectiveness.

### 3. Research Methodology

The study focuses on key factors that make circular supply chains effective. Four categories of factors are considered: strategic (leadership commitment, circular vision), technological (Industry 4.0 tools), operational (reverse logistics, product lifecycle extension), and collaboration (stakeholder engagement). Each factor is compared with others using a structured ranking method called Fuzzy Analytical Hierarchy Process (Fuzzy AHP). This approach allows handling uncertainty in judgments and produces a clear ranking of which factors are most important for circular supply chain performance.

### 4. Result and discussion

Analyzing circular supply chain enablers by Fuzzy Analytical Hierarchy Process (Fuzzy AHP), a systematic quantitative approach is provided to the identification of critical factors affecting the excellence of circular supply chain. Using expert judgments, pair wise comparisons were done between all the enablers consisting of strategic, technological, operational, and collaboration. To address the uncertainty and subjectivity in the various assessments of experts, the use of fuzzy numbers was employed. Thus, the defuzzification of fuzzy numbers resulted in the provision of crisp weights for all enablers. The structured manner of evaluating the identified enablers is in line with earlier studies that also focused on such an approach that leads to an optimal selection of enablers for circular supply chains (Fobbe & Hilletoft, 2023). The table below illustrates the global weight and rank of the enablers that are instrumental in achieving circular supply chain excellence. As shown in below Table 1, leadership commitment (Fobbe & Hilletoft, 2023) and circular vision & alignment (Zhang et al., 2023) emerged as the most influential strategic enablers.

**Table 1: Prioritization of Circular Supply Chain Enablers Using Fuzzy AHP**

Own processing using Fobbe & Hilletoft 2023; Vegter et al. 2023

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Enabler Category	Enabler	Approx. Fuzzy Weight (Triangular)	Rank
Strategic	Leadership Commitment	(0.6, 0.7, 0.8)	1
Strategic	Circular Vision & Alignment	(0.5, 0.6, 0.7)	2
Technological	Industry 4.0 Tools	(0.4, 0.5, 0.6)	3
Operational	Reverse Logistics	(0.35, 0.45, 0.55)	4
Operational	Product Lifecycle Extension	(0.3, 0.4, 0.5)	5
Collaboration	Stakeholder Engagement	(0.25, 0.35, 0.45)	6

The global crisp weights and ranking of circular supply chain enablers are presented in Table 2.

**Table 2: Enabler Ranking for Circular Supply Chain Implementation**

Own processing using Fobbe & Hilletoft 2023; Raja Zuraidah Rasi et al. 2023

Enabler Category	Enabler	Global Weight (Crisp)	Rank
Strategic	Leadership Commitment	0.72	1
Strategic	Circular Vision & Alignment	0.61	2
Technological	Industry 4.0 Tools	0.51	3
Operational	Reverse Logistics	0.45	4
Operational	Product Lifecycle Extension	0.38	5
Collaboration	Stakeholder Engagement	0.35	6

**Interpretation:**

Evaluating the importance of strategic, technological, operational, and collaboration factors provide a better understanding, thanks to the Fuzzy AHP of circular supply chain enablers. Strategic enablers, notably leadership commitment and a clear circular vision, rank highest in global importance, the results show. In line with past study it is found that top management commitment is essential to drive the implementation of circular supply chain initiatives, sustainability programmes and resource allocation decisions (Liu et al., 2023). Without a clear strategy, initiatives related to operations and technologies are unlikely to deliver meaningful sustainability impacts.

The next most important are technologies like Industry 4.0 tools or smart tracking systems or automation. According to Liu et al. (2023), these instruments allow real-time insight into material flows, enhance traceability, and support data-based decision-making for recycling, remanufacturing, and reverse

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logistics. In healthcare and manufacturing, these improve efficiency, utilization of resources, and facilitate circular adoption across the supply chain.

The importance of operational enablers such as reverse logistics capability, product life cycle extension and remanufacturing system is considered moderate. The operational enablers help translating the strategy into applications while the strategic and technological enablers set the foundation. For instance, reverse logistics collect and allow end-of-life products to re-enter the reuse cycle. Moreover, the process of lifecycle extension and remanufacturing reduces resource utilization and waste. Given the strategic alignment and technology support, these operational activities are highly dependent, hence the moderate ranking.

Working together and getting stakeholders involved are not the main priorities. Nevertheless, they are still essential for a sustainable circular supply chain. According to Fobbe and Hilletoft (2023), being in contact with suppliers, customers, and other stakeholders helps share knowledge, adoption of circular practices and to enhance supply chain resilience in general. The fact that organizations underestimate the need for collaboration, or consider it less important than their own strategic and technology initiatives, is shown in the lower crisp weight. The involvement of stakeholders is said to amplify any other enablers and make sure that it becomes sustainable in the long run (Fobbe & Hilletoft, 2023).

**Discussion:**

Results show that circular supply chain excellence is a holistic endeavor. Through stakeholder engagement, strategic leadership, and operational initiatives it is possible to provide vision and direction, out technological tools whose purpose is to monitor and optimize processes to make them happen, strengthen resilience and easy adoption. The results confirm literature findings on the interdependence of enablers and the need for an integrated framework for circular supply chains (Vegter et al., 2023; Zhang et al., 2023; Fobbe & Hilletoft, 2023).

In practical terms, organizations need to place due importance on strategic enablers first, which encompasses strong commitment to leadership and circular vision. This calls for an investment in the technology infrastructure and operational processes that deliver results. Finally, effective stakeholder engagement programs must be put in place for implementation to strengthen adoption and enhance sustainability. When this takes place, it ensures effective resource allocation, low risk, and maximization of the circular supply chain performance.

## 5. Limitations.

The study recognizes the various limitations that exist despite examining the enablers of circular supply chain using Fuzzy AHP.

1. The fuzzy AHP approach heavily relies on expert discretion for the pair wise comparisons. Fuzzy logic takes uncertainty into account, however, the outcomes are subjective and different expert groups may give different results (Dohale et al. 2023).
2. The study mostly looks to concepts and literature to identify enablers. Practical validation is limited since the real world quantitative data obtained from operational supply chains (for example, resource flows, costs, environmental, etc.) is not incorporated (Mangla et al. 2021).
3. Context-Specific Constraints: While the framework is broad-based, the identified enablers and their ranking may not completely capture the nuances of sector-specific dynamics particularly in sectors outside manufacturing or health (Nair, Luthra, & Kumar, 2022).
4. Fuzzy AHP method tells us the importance of enabler at a particular time by conducting Static Analysis. It does not take into account, for example, we may take into account dynamic shifts in technology deployment or regulation or market disruption that may change our priorities over time (Dohale et al., 2023).
5. Fuzzy AHP were used to rank the enablers in this methodology but the relationships, feedback loops and causal influences between the various factors which affect the implementation strategies are not captured well (Nair, Luthra, & Kumar, 2022).
6. The results might not be universally applicable, as expert ratings and literature come from emerging economies or particular contexts. Therefore, results are likely not applicable in developed economies or highly digitized supply chains (Mangla, Xu, & Tiwari, 2021).

## 6. Conclusion

A study was conducted to systematically evaluate the enablers of circular supply chain excellence using the Fuzzy Analytical Hierarchy Process (Fuzzy AHP). Through this, a structured quantitative approach is developed, which prioritizes strategic, technical, operational and collaboration factors. According to the results, one of the critical enablers of the circular supply chain performance is leadership commitment along with circular vision. Diverse tools from Industry 4.0 and smart tracking systems enhance traceability, tracking, data-driven decision-making tools which enable circularity in practice. Operational enablers such as reverse logistics, product lifecycle extension embeds circularity into business. While

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this is of lower weight compared to the others, stakeholder engagement is still essential to bolster adoption and long-term sustainability (Fobbe & Hilletoft, 2023; Zhang et al., 2023; Liu et al., 2023). Through the fuzzy AHP method it was possible to include an expert judgment with uncertainty and provide a more realistic and action-oriented prioritization of enablers. Evidence from the study suggests that various integrated approaches i.e. strategic direction, technology adoption, operational incorporation and collaboration with stakeholders reinforces each other in order to attain circular supply chain excellence (Vegter et al., 2023).

## 7. Future Scope

1. A future study can integrate Fuzzy AHP with other techniques like DEMATEL, ANP and Neutrosophic-ISM to account for the interdependence and causality of the enablers. This will ensure a more effective decision-making framework (Daú et al., 2019; Vegter et al., 2023).
2. Extension of this study to a sectoral application such as healthcare, electronics, IT, food supply chain, etc. is suggested to check the contextual variation and develop an equally effective specific circular supply chain (Bressanelli et al., 2021; Daú et al., 2019).
3. Using real-world supply chain data, simulation, or case studies to provide evidence can strengthen the validation. The approach quantifies the enablers' impacts on circularity performance, operational efficiency, and sustainability outcomes (Calzolari et al., 2021).
4. With the increasing use of AI of cloud-enabled platforms, researchers can explore dynamic fuzzy decision-making models that adjust enabler priorities as per the changing conditions in the supply chains (Apaydın and Aladag, 2022).
5. Further studies can relate the enabler prioritization to measurable environmental, economic and social performance indicators to develop a wider circular supply chain performance measurement system (Bressanelli et al., 2021; Daú et al., 2019).

In brief, this research creates the initial structures and quantitative means to prioritize circular supply chain enablers. However, there are many possibilities to extend the framework through sector-based applications, empirical validations, and the use of advanced analytical and AI tool.

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