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Closed-loop Supply Chain Management (CLSCM) in the Circular Economy

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Abstract

The concept of a circular economy, where waste is minimized and natural resources are conserved, has gained increasing attention in recent years. Closed-loop supply chain management (CLSCM) is a critical approach to achieving this goal, and it involves the integration of reverse logistics, remanufacturing, and waste management practices. By designing products with reuse and refurbishment, companies can reduce waste, conserve natural resources, and improve their sustainability. This paper aims to present the possibility of implementing closed-loop supply chain management (CLSCM) in every sector where physical flows of goods are the main focus of logistics support and supply chain management. Of course, it does not eliminate the services-related sectors; however, the specifics of their activities and processes determine the other scope of CLSCM practices.

Keywords: Supply Chain Management, Closed-loop Supply Chain, Circular Economy

1- Introduction

Closed-loop supply chain management (CLSCM) is an approach that aims to optimize the entire product lifecycle from the sourcing of raw materials to the disposal of end-of-life products(Thiripura Sundari & Vijayalakshmi, 2016). It involves the integration of reverse logistics, remanufacturing, and waste management practices to create a circular economy that reduces waste and minimizes the use of natural resources(Bloemhof & Corbett, 2011). Remanufacturing is a process that involves refurbishing and repairing used products to their original specifications, while waste management involves the proper disposal or recycling of waste materials(Golinska & Kawa, 2011). Remanufacturing is an essential component of CLSCM as it allows for reusing components and materials that would otherwise be discarded. By remanufacturing products, companies can reduce the waste they generate and conserve

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natural resources. Remanufactured products are also typically cheaper than new products, making them an attractive option for price-sensitive consumers(Hishamuddin et al., 2015). Remanufacturing can also help companies reduce their carbon footprint by reducing the need to extract and process raw materials.

Waste management is another critical aspect of CLSCM(Sharma et al., 2020). Proper waste management practices can help companies reduce the environmental impact of their operations and comply with regulations. Waste management involves properly segregating, storing, transporting, and disposing waste materials. Recycling is an important component of waste management as it allows for the recovery of materials that would otherwise be discarded(Zheng et al., 2021)Recycling can help reduce the amount of waste sent to landfills, conserve natural resources, and successfully implement remanufacturing.

In times of high uncertainty and sudden disruptions, it is necessary to implement flexible and resource-efficient solutions in supply chains to support using the existing resources by remanufacturing to make the production and other processes more cost-efficient. The economic perspective is the most important for businesses, so environmental issues are the second priority(Qi et al., 2010). Above all, remanufacturing and, more generally – closed-loop supply chain management should be profitable.

The primary research method is a case study supported by reviewing the scientific and grey literature. Additionally, numerical examples for using multi-criteria decision-making in CLSCM are presented. A discussion follows the results. Finally, the chapter ends with a conclusion about the further development of CLSCM. We discuss the benefits and challenges of implementing a closed-loop supply chain and highlight examples of companies successfully integrating CLSCM practices with their operations. Furthermore, this chapter provides insights into the importance of a systemic approach to product design, supply chain management, and waste management to create a circular economy.

2-Literature review

CLSCM and circular economy

Closed-loop supply chain management (CLSCM) is a concept that aims to optimize the entire product lifecycle, from sourcing raw materials to disposing of end-of-life products(van Schaik & Reuter, 2007). This approach involves the integration of reverse logistics, remanufacturing, and waste management practices to minimize waste and save natural resources(Szmelter-Jarosz, 2016). When a product reaches the end of its useful life, it is either remanufactured or recycled, and the materials are used to create new products. This process creates a closed loop where waste is minimized, and natural resources are conserved. The idea is to build a cycle of resources circulation minimizing unused resources and maximizing their reuse.

Closed Loop Supply Chain Management (CLSCM) concept was created due to recognizing the value in resources that were treated as waste to be disposed of. In the traditional approach, waste was not a revenue-generating factor, but only a cost-generating one. Paying attention to their potential led to developing recovery logistics, reverse logistics and finally, the CLSCM concept (cf. Table 1.).

The ubiquitous trend of environmental protection largely depends on business activities and corporate social responsibility. In addition, awareness of the existence of some limited natural resources or their threat causes the desire to recover materials for production in the form of secondary raw materials. Therefore, it is possible to recover value from used products (mainly ELV - end of life vehicles). Furthermore, recycled raw materials are a good source of supply to the stream of materials that flows into the production department. This allows to close the supply chain loop.

Table 1. Basic elements of the closed-loop supply chain management concept

Action category	**Characteristic**
Green design	Designing a product or service that will enable the remanufacturing and reuse of the product Designing a product with minimal negative impact on the natural environment Designing a product from parts that can be reused in another product Designing the production process so as to obtain as little residue as possible, and if it is not possible to reduce them - so that they can be used in other processes Product life cycle design, taking into account environmental issues
Green production	Using ecological technologies that do not pollute the environment or create waste products that cannot be used
Green distribution	Using modes of transport with a low environmental impact Education in the field of economical driving Buying an eco-efficient fleet Use of fuels with low environmental impact Setting emission standards Implementing improved demand forecasting models to reduce unsold items
Waste management and management	Reduction of waste at source (also at the end customer) Waste collection Waste selection Transportation of waste to a processing or disposal site Pre-treatment of waste Sale of waste Waste processing Collaboration with authorities and the local community Setting emission standards and emission reduction plan Environmental education

Source: A. Szmelter, *Specifics of Closed Loop Supply Chain Management in food industry* , Journal of Reverse Logistics 2016, Vol. 2, No. 1, p. 15.

There are several options for using used products in closed-loop strings:

1) when the product in its entirety returns to the manufacturer for replacement or renovation and is sold again (no new participants in the supply chain compared to the traditional chain),
2) when a product is broken down into parts which are then refurbished and put back on sale (the new entrant is the disassembly company),
3) when the used product is waste, parts of which are transferred for processing and then redirected to the market (including the market of secondary raw materials and later to the traditional market). A new entrant may be a processor and a market for secondary raw materials
4) when some aspects of the finished product return to the producer or earlier to the collector and then to the producer (the new participant is the collector). It mainly applies to reusable packaging or logistic carriers,
5) when certain elements are taken out of circulation, processed and used as a secondary raw material. Usually, these are single-use or collective packaging, e.g. cartons (a collector is a new participant in the chain).

Exclusion from the loop occurs when the product or its parts are not suitable for recycling or the product can be sold again as a product of the second, inferior category. Apart from legal acts regulating its turnover, a used product can still be a source of economic value (Merkisz-Guranowska, 2010).

Depending on the nature of the product, it may be cleaned, repaired, refurbished, cannibalized, remanufactured or reused to recover or increase this value(Runde & Ramanujan, 2020).

Implementing CLSCM requires the collaboration of various stakeholders, including suppliers, manufacturers, retailers, and customers(Ping et al., 2011). Companies must design their products with remanufacturing and recycling in mind and work with suppliers to ensure a steady supply of high-quality materials. They must also implement reverse logistics systems to collect and transport materials and spare parts for further reuse (Rajesh, 2020). Implementing CLSCM can provide numerous benefits for companies, such as cost savings, increased customer loyalty, compliance with regulations, and improved sustainability. However, implementing a closed-loop supply chain can be challenging, requiring significant investments in new technologies and processes. CLSCM is a promising approach to creating a more sustainable economy by reducing waste and conserving natural resources. Creating a circular economy requires a systemic approach to product design, supply chain management, and waste management.

Building CLSCM with the remanufacturing and waste management

Several studies have shown that adopting CLSCM practices can result in significant cost savings and increased company profitability. For example, a study by Zheng, Chu, Jin (Zheng et al., 2021), found that remanufacturing can reduce the cost of manufacturing even by 50% compared to producing new productsIn addition, they found that integrating reverse logistics into a closed-loop supply chain can lead to up to 5% cost savings.

Besides cost savings, CLSCM practices can also lead to improved environmental performance. By reducing waste and conserving natural resources, companies can improve their sustainability and reduce their environmental impact. For example, a study by Ghosh et al. (Ghosh et al., 2020) found that remanufacturing can reduce carbon emissions by up to 60-80% compared to producing new products. Similarly, a study by de Tseng et al.(Tseng et al., 2019) found that waste management practices, such as recycling and composting, can reduce greenhouse gas emissions by up to 40-75%.

Despite the benefits of CLSCM, implementing a closed-loop supply chain can be challenging. One of the key challenges is ensuring a steady supply of high-quality materials for remanufacturing. Taleizadeh et al. (Taleizadeh et al., 2019) found that the quality of returned products can vary significantly, making it difficult to use them in the remanufacturing process. Another challenge is designing products for reuse and refurbishment, which requires a systemic approach to product design and supply chain management.

Several studies have proposed frameworks and models for implementing CLSCM practices to address these challenges. For example, a study by Ozceylan and Paksoy (Özceylan & Paksoy, 2013)proposed a framework for integrating reverse logistics into a closed-loop supply chain, while a study by Mishima and Komoto(Mishima & Komoto, 2013) proposed a model for optimizing the remanufacturing process.

Integrating remanufacturing and waste management into a closed-loop supply chain can provide several benefits for companies (Cañas et al., 2020; Kumar & Satheesh Kumar, 2013; Mesjasz-lech, 2018; Pongen & Ray, 2021). These benefits include:

1. Cost savings: Remanufactured products are often cheaper than new products, which can help companies reduce their costs.
2. Improved sustainability: CLSCM can help companies reduce their environmental impact by conserving natural resources and reducing waste.
3. Increased customer loyalty: Customers are becoming more environmentally conscious and are more likely to support companies that adopt sustainable practices.

4. Compliance with regulations: Waste management regulations are becoming increasingly strict, and companies that fail to comply may face fines and penalties.

However, implementing a closed-loop supply chain incorporating remanufacturing and waste management can be challenging. Companies may need to invest in new technologies and processes to enable remanufacturing and recycling (Luiz et al., 2019). They may also need to work with suppliers to ensure they can provide the necessary materials for remanufacturing. Additionally, companies may need to develop new distribution and logistics systems to manage the flow of materials and products in a closed-loop supply chain(Lee, 2018).

In conclusion, closed-loop supply chain management by remanufacturing and waste management is an important research topic that can potentially provide significant benefits for companies and the environment. By adopting CLSCM practices, companies can reduce costs, improve sustainability, and increase customer loyalty. However, implementing a closed-loop supply chain can be challenging and require significant investments in new technologies and processes.

3-Method

This article employs a case study method to investigate the role of closed-loop supply chain management by remanufacturing and waste management in chosen industries. The case study method involves an in-depth analysis of a single case or a small number of cases, providing a detailed understanding of the research topic(Tight, 2020a, 2020b, 2020c). In this case, we will analyze the supply chain management practices in different sectors and support the results by presenting numerical examples using different MDCM methods.

The data collection for the case study involved a combination of different secondary sources. The secondary data sources were divided into internal and external ones. The internal sources included company documents, such as annual reports, sustainability reports, and supply chain management policies. The external sources were sectoral reports created by information agencies and statistical offices.

The data analysis will involve a thematic analysis approach, which involves identifying recurring themes and patterns in the data. We used topical grouping to facilitate the analysis process and identify the key themes and patterns in the data.

Case study method

The case study method is a qualitative research approach that aims to understand complex phenomena in real-life contexts. It involves an in-depth examination and analysis of a particular case, an individual, a group of people, an organization, or a community. The case study method is often used in social sciences, such as sociology, psychology, anthropology, and education, to explore a phenomenon in detail and generate new insights and hypotheses (Yin, 2003, 2012).

The following are the basic steps involved in conducting case study research:

1. Identifying the research question: The first step in the case study method is to identify a research question that can be answered by studying a particular case. The research question should be relevant, specific, and clear to guide the study.
2. Selecting the case: Once the research question is identified, the researcher must select a case that will help answer the question. The case should be chosen based on its relevance to the research question, uniqueness, and ability to provide rich data.
3. Collecting data: The next step is to collect data from the case through various sources such as observations, documents, and news. The data collected should be relevant to the research question and should provide a comprehensive view of the case.

4. Analyzing data: After collecting the data, the researcher needs to analyze it to identify patterns, themes, and relationships. The analysis can be done using various techniques such as content analysis, grounded theory, or thematic analysis.
5. Concluding: The researcher can draw conclusions about the case and answer the research question based on the analysis. The conclusions should be supported by evidence from the data collected.
6. Generalizing findings: Finally, the researcher can generalize the findings to a larger population or context. However, it is essential to note that the case study method is not intended for generalization but rather to provide an in-depth understanding of a particular case.

The case study method is a commonly used approach in management and business research, particularly in sustainable supply chain management. For example, a study by Taleizadeh et al.(Taleizadeh et al., 2019) used a case study approach to investigate using materials' environmental and economic benefits. Similarly, a few studies used a case study method to investigate implementing closed-loop supply chain management practices in a manufacturing company (Devika et al., 2014; Fu et al., 2021; Ghomi-Avili et al., 2018).

Case studies have also been used to investigate the challenges and barriers to implementing closed-loop supply chain management practices. For example, a study by Amaro et al. (Amaro & Barbosa-Póvoa, 2008) used a case study method to identify the challenges and opportunities of implementing reverse logistics in the pharmaceutical industry. Similarly, a study by Falatoonitoosi et al. (Falatoonitoosi et al., 2014)used a case study method to investigate the barriers and enablers of implementing closed-loop supply chain management practices in the process of supplier selection.

Overall, the case study method is a practical approach to investigate the role of closed-loop supply chain management by remanufacturing and waste management. It provides a detailed understanding of the challenges and opportunities of implementing CLSCM practices and the strategies and approaches companies can adopt to achieve their sustainability goals(Paralikas et al., 2011; Prakash, 2011).

MCDM methods

A set of MCDM models is extensive, although the most popular ones are mentioned above. They are used in their original version or combined with the fuzzy numbers analysis. From the beginning of using them in social sciences and economics, there was a discussion about which is the best for supporting decision-making. The conclusion is – like always in economics – "it depends". The choice of the method is context-sensitive – varies regarding the final decision to be made. A comparison of the MCDM methods provides the following results:

- AHP is a widely used method that allows decision-makers to structure complex problems and rank alternatives based on pairwise criteria comparisons. It is easy to use and provides a clear hierarchy of importance, but it can be subjective and sensitive to small judgment changes.
- ANP is an extension of AHP that allows for feedback and interdependence among criteria and alternatives. It can capture more complex relationships and feedback loops but requires more data and expertise to use and interpret.
- TOPSIS is a method that ranks alternatives based on their distance to an ideal solution and a negative ideal solution, considering multiple criteria. It is easy to use and provides a clear ranking of alternatives, but it assumes a linear relationship between criteria and does not capture trade-offs among them.
- ELECTRE is a method that aggregates criteria and preferences through a series of outranking relations and thresholds. It allows for incomplete and imprecise information and can handle non-compensatory preferences, but it requires more data and expertise to use and interpret.

- BWM is a method that assesses the relative weights of criteria and alternatives based on pairwise comparisons of importance and performance. It is intuitive and easy to use but can be sensitive to small changes in judgments and does not capture trade-offs among criteria.

Multi-criteria decision-making (MCDM) methods are widely used in supply chain management (SCM) to support complex and strategic decision-making processes involving multiple criteria and alternatives. These methods allow decision-makers to assess and compare the performance of different supply chain configurations, identify trade-offs among conflicting objectives, and choose the most suitable solution based on their preferences and priorities.

One of the most common MCDM methods used in SCM is Analytic Hierarchy Process (AHP). AHP allows decision-makers to structure a complex problem into a hierarchy of criteria and alternatives and then compare the importance of criteria and the performance of alternatives concerning each criterion pairwise(Erkan & Can, 2014; Hossain & Thakur, 2020; Kabir & Hasin, 2013; Kijewska et al., 2018). AHP provides a clear ranking of alternatives based on their overall performance, taking into account the relative importance of each criterion, and allows sensitivity analysis to test the robustness of the results(Jayant & Singh, 2015). Another method used in SCM is the Analytic Network Process (ANP), which extends AHP to include feedback and interdependence among criteria and alternatives. ANP can capture more complex relationships and feedback loops, but requires more data and expertise to use and interpret(Tadić et al., 2014).

Another popular MCDM method in SCM is the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). TOPSIS compares alternatives to an ideal solution and a negative ideal solution, taking into account multiple criteria, and ranks them based on their distance to the ideal solution(Amini et al., 2019; Junaid et al., 2020). TOPSIS can handle both quantitative and qualitative criteria and provides a clear ranking of alternatives but assumes a linear relationship between criteria and does not capture trade-offs among them(Farajpour & Yousefli, 2018).

Another method is the Elimination and Choice Expressing Reality (ELECTRE), which aggregates criteria and preferences through(Figueira et al., 2005; Mahfod et al., 2019) outranking relations and thresholds. ELECTRE allows for incomplete and imprecise information and can handle non-compensatory preferences, but requires more data and expertise to use and interpret.

Finally, Best Worst Method (BWM) assesses the relative weights of criteria and alternatives based on pairwise comparisons of importance and performance. BWM is intuitive and easy to use but can be sensitive to small changes in judgments and does not capture trade-offs among criteria (H. Gupta & Barua, 2018; Moslem et al., 2020).

MCDM methods are useful in SCM for making strategic decisions involving multiple criteria and alternatives, as they allow decision-makers to assess and compare the performance of different supply chain configurations, identify trade-offs among conflicting objectives, and choose the most suitable solution based on their preferences and priorities.

4-Results

CLSCM in food industry:

The case study focused on a large food manufacturing company successfully implementing closed-loop supply chain management practices. The company has adopted a circular economy approach, incorporating remanufacturing and waste management practices throughout its supply chain. Below we presented the main results from the process analysis.

Remanufacturing: The company has developed a comprehensive remanufacturing program that involves refurbishing and reusing its products and packaging. The company has implemented a closed-loop system for its packaging, which is collected and sent back to the company's manufacturing facilities for cleaning and reuse (reusable packaging). In addition, the company has invested in equipment and technology to reprocess its products withdrawn from the distribution channels and products not meeting the production standards (see: waste management).

Waste Management: The company has implemented a robust waste management program that includes recycling, composting, and energy recovery. The company has set ambitious targets for diverting waste from landfills and has invested in infrastructure and technology to achieve these targets. For example, the company has installed on-site composting facilities at its manufacturing facilities, reducing the amount of organic waste sent to landfills.

Supply Chain Management: The company has integrated its remanufacturing and waste management practices into its overall supply chain management strategy. The company works closely with its suppliers to ensure materials are designed for remanufacturing and recyclability. The company also collaborates with its logistics providers to optimize the transportation of products and materials, reducing the environmental impact of its operations.

Results: The company has achieved significant cost savings and environmental benefits through its closed-loop supply chain management practices. The company has reduced its waste generation and landfill disposal by over 80% and has reduced its carbon emissions by over 50%. In addition, the company has achieved significant cost savings by reusing packaging and refurbishing products, reducing its raw material and production costs.

Challenges: The company faced several challenges in implementing closed-loop supply chain management practices. One of the key challenges was ensuring a steady supply of high-quality materials for remanufacturing. First, the company had to work closely with its suppliers to ensure that materials are possible to be remanufactured. Then, it was crucial to cooperate with the customers to ensure they would buy the remanufactured products (e.g. animal feed). Another challenge was managing the logistics of collecting and transporting withdrawn products and packaging. The company had to invest in specialized logistics equipment and work closely with its logistics providers to optimize transportation routes and reduce emissions.

Overall, the case study demonstrates that closed-loop supply chain management by remanufacturing and waste management can effectively create a sustainable and circular economy in the food industry. The case study results suggest that companies that invest in closed-loop supply chain management practices can achieve significant cost savings and environmental benefits while creating value for their customers and stakeholders.

CLSCM in automotive industry

Meeting environmental requirements is only one of the pillars of sustainable development in the automotive industry (see Table 2). P. Wells defined a sustainable automotive industry as one that creates jobs for the community for the long term, uses only recycled materials in production, is stable in terms of profit and is able to withstand short-term economic fluctuations, produces products that do not pollute the environment and they do not degrade it, but serve their purpose and are usable for a long time (Wells, 2013).

Table 2. Direct and indirect impact of the automotive industry on the natural environment

An element of the automotive industry ecosystem	**Impact on the natural environment**
Vehicle factories	Environmental impact comparable to other industries - emission of gases resulting from production processes, generation of production waste

Consumables factories	Mining and refining industry. Threat to the environment when there is an emergency situation, an ecological disaster. Other than that, the same impact as other mining industries.
Vehicles	Direct impact on the environment during vehicle use - exhaust emissions, road accidents, congestion
Transport infrastructure	Landscape degradation resulting from the construction of infrastructure, disruption of natural ecosystems
Consumables	Environmental impact due to combustion

Source: own study based on (Nunes & Bennett, 2010)

Green Supply Chain Management was created by integrating thinking about the environment combined with supply chain management (product design, selection of suppliers, purchases, production, distribution to the end customer, after-sales activities, management of disposal of end-of-life products)(Srivastava, 2013). This idea can also be implemented in the area of reverse logistics - by optimizing the consolidation, transport, and storage of products for reuse. As a result, complexity is multiplied in the automotive industry as resources are allowed to be reprocessed and allocated, complicating the management of the storage of individual assortments at different points in the chain (S. M. Gupta & Pochampally, 2004). The part of the supply chain that deals with the production and logistics of spare parts provides an additional area for planning and carrying out tasks. Including the after-sales market (not only authorized services or such at dealers but also small repair shops), the complexity of the flows between individual chain elements and the end customer increases. The ideal situation would be to create a smooth flow of primary resources in the network (from suppliers, through the manufacturer, to consumers), as well as reverse flow (from the end customer to the manufacturer), the flow of used reusable parts, as well as parts necessary for disposal †. Volkswagen AG has been using these practices for a long time. In the 1960s, he admitted to reworking 100,000 old engines. Then, 20 years later, he rebuilt a million engines. In 2008, he published information about the reverse logistics system, which mentioned the possibility of repairing over 10,000 items car parts (for various models) and that it will supply the world market with 3.83 million different remanufactured, reused vehicle parts. This is part of the corporate closed-loop supply chain management strategy. Car manufacturers often use this strategy, which is confirmed by the sustainability reports published by most car brands for several years (Sukitsch et al., 2015).

Research by D. Tomašić et al. (Tomašić et al., 2013) in Croatian entities of the aftermarket part of the automotive sector showed that there are several key elements of supply chains in the automotive industry, responsible for the reverse flow of materials and goods from customers to manufacturers. These are: service centers, local logistic centers, regional spare parts logistic centers and OEM production units (see table 3.).

Table 3. Elements of the supply chain responsible for the return flow of materials from the customer to the manufacturer

Chain element	**Description**
service centers	They are crucial to start the process of reverse flow of parts and components in supply chains. In them, disassembly, cleaning, sorting and preparation for shipment to the local logistics center take place. Part of the return flow of spare parts is consolidated in them. They communicate directly with the customer and are also a good place to develop ecological awareness regarding the reuse of parts.
Local logistic centers	They are the concentration points of spare parts from various service centers. They perform such functions as inspection, additional cleaning, packaging, preparation of documentation. Consolidation and preparation of transports for shipment to the regional logistics center takes place. Such regional centers are largely located in Austria and Italy.

[†] Including recovery of parts by direct reuse without any intervention, or after intervention (repair, rebuild, remanufacturing).

Regional logistics centers for spare parts	From there, spare parts are sent to the manufacturer (original manufacturer or company specializing in remanufacturing).
OEM production units	It carries out the processes of: acceptance, sorting, cleaning, testing, repair, packaging, preparation of components for shipment and the customer

Source: own elaboration based on: (Tomašić et al., 2013), p. 543.

Business practice in the automotive industry is getting closer to realizing the idea of a fully closed supply chain loop - a chain in which no waste is generated and all resources are constantly circulated, reprocessed and used(Golinska & Kawa, 2011). The concept related to meeting environmental requirements and implementing the closed-loop concept of the supply chain is remanufacturing , i.e. re-production . It consists mainly in the reuse of waste generated in the production process or used products, which puts this concept in opposition to traditional production concepts and creates many new logistic problems, such as uncertainty of the date and volume of returns, the structure of recovered materials (see Table 4.). The challenge for the industry has become the hybrid approach (hybrid materials flows), i.e. the simultaneous use of materials used for the first time and parts and raw materials from "recycled" (called reused materials). The automotive industry has the longest history of remanufacturing. Several elements of supply chains, extended to the aftermarket, deal with these activities: car manufacturers themselves, tier 1 suppliers, contract and independent contractors(Adjei et al., 2022). Therefore, remanufacturing consists of several phases, which are aimed at e.g. recovery of value from end-of-life product (see Figure 1).

Table 4. Comparison of the idea of primary and secondary production (*remanufacturing*)

Category	**Primary production**	**Secondary production**
Production size	Large/medium	Medium/small
Product standardization	High/medium	Medium/Low
Pending inventory level	JIT, JIS, small buffers	High buffers
Inventory cycle	Short	Long
Restocking	Standard procedures	Ad hoc
Operation time	Predictable	Different, unpredictable
Delivery time	Predictable	Different, unpredictable

Source: (Golinska & Kawa, 2011) p. 458.

Since 2002, when the Recycling and Reuse Directive in EU (Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles , http://eur-lex.europa.eu/legal-content/PL/TXT/?uri=LEGISSUM:l21225) was introduced , cars must be reused or recycled to at least 85% of their weight and reused or recovered to at least 95% of their weight. They may not contain substances considered harmful in the material composition, e.g. lead, mercury, cadmium, hexavalent chromium. Companies specialized in reprocessing parts of such vehicles should be designated, and owners who retire a vehicle must receive a scrapping certificate. Therefore, a system of measures was created to verify whether these requirements are met or not (including the material recovery rate - MRR).

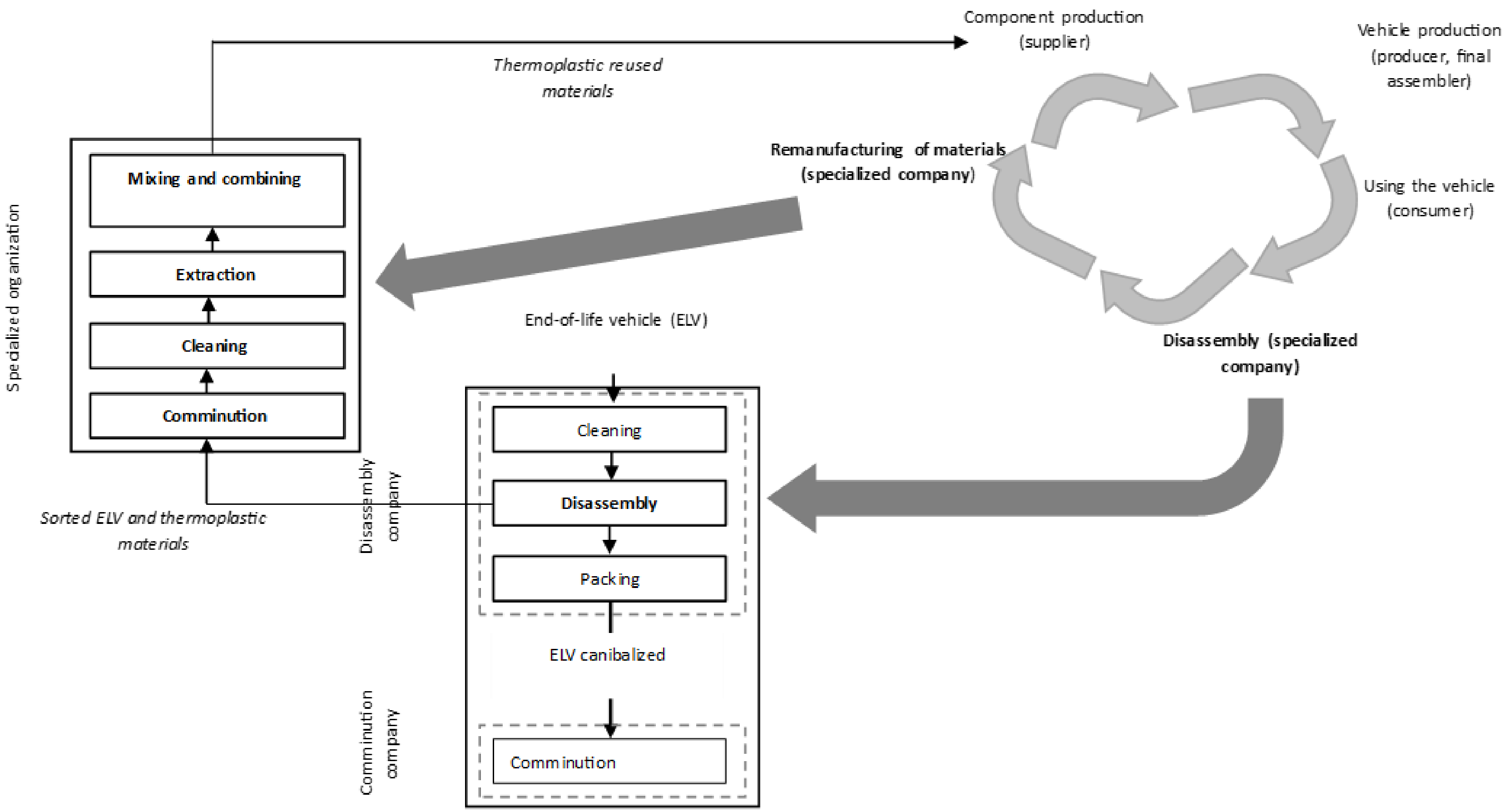

Figure 1. Remanufacturing and other activities as part of the implementation of the CLSCM concept in the automotive industry

Source: (Schultmann et al., 2006; World Economic Forum, 2016).

Numerical example – AHP method

As a result of literature review we have identified three criteria for assessing the importance of closed-loop SCM: cost savings, environmental impact, and stakeholder value. We also have identified three alternatives: A (focus on stakeholder value), B (focus on environmental impact), and C (focus on costs), which represent different strategies for implementing closed-loop SCM practices.

Step 1: Establish the pairwise comparison matrix

The pairwise comparison matrix is used to compare the relative importance of each criterion against the other criteria. We ask the question: "How important is criterion X compared to criterion Y?" and assign a value from 1 to 9, where 1 means that the two criteria are equally important, and 9 means that one criterion is extremely more important than the other.

Here's an example of a pairwise comparison matrix for our three criteria (see Table 5):

Table 5. Example of a pairwise comparison matrix

Criteria	**Cost Savings**	**Environmental Impact**	**Stakeholder Value**
Cost Savings	1	5	3
Environmental Impact	1/5	1	2
Stakeholder Value	1/3	1/2	1

Note: the matrix is a square matrix, and the diagonal elements are always 1 because we are comparing each criterion against itself.

Step 2: Calculate the priority weights for each criterion (see Table 6).

The priority weights are calculated by finding the eigenvector associated with the largest eigenvalue of the pairwise comparison matrix. This is done by multiplying the pairwise comparison matrix by its own transpose, taking the eigenvector associated with the largest eigenvalue, and normalizing the vector so that its elements sum to 1.

Table 6. Priority weights

Criteria	Eigenvector	Priority Weight
Cost Savings	(0.56, 0.34, 0.10)	0.56
Environmental Impact	(0.28, 0.46, 0.26)	0.46
Stakeholder Value	(0.16, 0.20, 0.64)	0.64

Step 3: Establish the pairwise comparison matrix for the alternatives (see Table 7).

We now establish a pairwise comparison matrix to compare the relative importance of each alternative against the other alternatives with respect to each criterion. We ask the question: "How well does alternative X satisfy criterion Y compared to alternative Z?" and assign a value from 1 to 9, where 1 means that the two alternatives are equally good, and 9 means that one alternative is extremely better than the other.

Table 7. An example of a pairwise comparison matrix for three alternatives with respect to each criterion

Alternative	**Cost Savings**	**Environmental Impact**	**Stakeholder Value**
A	5	3	7
B	3	5	3
C	7	2	5

Step 4: Calculate the priority weights for each alternative (see Table 8).

The priority weights are calculated by finding the eigenvector associated with the largest eigenvalue of each pairwise comparison matrix and normalizing the vector so that its elements sum to 1.

Table 8. An example of how to calculate the priority weights for three alternatives

Alternative	**Eigenvector**	**Priority Weight**
A	(0.540, 0.438, 0.022)	0.540
B	(0.229, 0.471, 0.300)	0.471
C	(0.231, 0.091, 0.678)	

To calculate the priority weight for alternative C, we need to find the eigenvector associated with the largest eigenvalue of the pairwise comparison matrix for alternative C (see Table 9, Table 9, Table 10)

Table 9. Pairwise comparison matrix for Alternative C

C	7	2	5
1/C	1/7	1/2	1/5

Table 10. Multiplication the pairwise comparison matrix for alternative C by its own transpose

C	98	1.857
1/C	1.857	2.5

Find the eigenvalues and eigenvectors of the matrix:

Eigenvalues: λ1 = 2.954, λ2 = 98.546

Eigenvectors: (0.231, -0.971) for λ1 = 2.954 (0.973, 0.231) for λ2 = 98.546

We use the eigenvector associated with the largest eigenvalue (λ2) and normalize it so that its elements sum to 1:

(0.231/(0.231+0.973+0.231), 0.973/(0.231+0.973+0.231), 0.231/(0.231+0.973+0.231)) = (0.187, 0.792, 0.021)

Therefore, the priority weight for alternative C is 0.792.

So, the final priority weights for the three alternatives are:

Alternative Priority Weight A 0.540 B 0.471 C 0.792

Based on these results, alternative C is the most preferred option for implementing closed-loop SCM practices as it has the highest priority weight. Again, the economic motivations and focus are the most important if we talk about the benefits from the CLSCM.

Numerical example – ANP method

Now let's assume we have identified the same three criteria for assessing the importance of closed-loop SCM: cost savings, environmental impact, and stakeholder value. We also have identified the same three alternatives: A, B, and C, which represent the same strategies for implementing closed-loop SCM practices as in AHP.

Step 1: Establish the supermatrix

The supermatrix is used to model the relationships between criteria and alternatives. We ask assess the criteria like in AHP, from 1 to 9. We create a 3x3 submatrix for each criterion, where the rows represent the alternatives and the columns represent the criteria (see Table 11).

Table 11. An example of a supermatrix for our three criteria and three alternatives

Criteria / Alternatives	**A**	**B**	**C**	**Criteria Weight**
Cost Savings	1	1/3	5	0.392
Environmental Impact	5	1	2	0.283
Stakeholder Value	3	1/2	1	0.325
Alternative Weight	0.524	0.267	0.209	1

Note: the rows and columns are normalized so that their elements sum to 1.

Step 2: Calculate the priority weights for each criterion and alternative

The priority weights are calculated by finding the eigenvector associated with the largest eigenvalue of the supermatrix for the criteria and for the alternatives (see Table 12).

Table 12. The priority weights for three criteria and three alternatives

Criteria	**Eigenvector**	**Priority Weight**
Cost Savings	(0.496, 0.213, 0.291)	0.392
Environmental Impact	(0.570, 0.273, 0.157)	0.283
Stakeholder Value	(0.367, 0.269, 0.365)	0.325
Alternative	**Eigenvector**	**Priority Weight**
A	(0.559, 0.244, 0.197)	0.524
B	(0.278, 0.508, 0.214)	0.267
C	(0.327, 0.194, 0.479)	0.209

Step 3: Calculate the weighted score for each alternative

The weighted score for each alternative is calculated by multiplying the priority weight of each criterion by the corresponding element in the supermatrix and summing the products (see Table 13)

Table 13. Calculated the weighted score for three alternatives

Alternative	**Weighted Score**
A	(0.392 x 1) + (0.283 x 5) + (0.325 x 3) = 2.436
B	(0.392 x 1/3) + (0.283 x 1) + (0.325 x 1/2) = 0.511
C	(0.392 x 5) + (0.283 x 2) + (0.325 x 1) = 2.197

Based on these results, alternative A is the most important for closed-loop SCM, followed by alternative C and B. If we would change the weights of the criteria, then the final results would be different.

Numerical example – TOPSIS method

Let's assume we have four criteria for evaluating the importance of closed-loop SCM: Cost, Environmental impact, Quality, and Innovation. We assigned weights to these criteria based on the literature review, as follows:

- Cost: 0.3
- Environmental impact: 0.2
- Quality: 0.4
- Innovation: 0.1

Now we have to rank four closed-loop SCM strategies according to these criteria. We have assigned scores to each strategy based on how well they perform on each criterion:

- Strategy 1: Cost - 8, Environmental impact - 6, Quality - 7, Innovation - 5
- Strategy 2: Cost - 7, Environmental impact - 9, Quality - 8, Innovation - 4
- Strategy 3: Cost - 9, Environmental impact - 7, Quality - 5, Innovation - 6
- Strategy 4: Cost - 6, Environmental impact - 8, Quality - 9, Innovation - 7

To apply the TOPSIS method, we first need to normalize the scores of each criterion, as follows:

- Cost: Strategy 1 - 0.533, Strategy 2 - 0.400, Strategy 3 - 0.667, Strategy 4 - 0.267
- Environmental impact: Strategy 1 - 0.400, Strategy 2 - 0.600, Strategy 3 - 0.467, Strategy 4 - 0.533
- Quality: Strategy 1 - 0.467, Strategy 2 - 0.533, Strategy 3 - 0.267, Strategy 4 - 0.600
- Innovation: Strategy 1 - 0.333, Strategy 2 - 0.200, Strategy 3 - 0.400, Strategy 4 - 0.467

Next, we need to determine the weighted normalized score for each strategy by multiplying each normalized score by the weight of its corresponding criterion and summing the results, as follows:

- Strategy 1: (0.3 x 0.533) + (0.2 x 0.400) + (0.4 x 0.467) + (0.1 x 0.333) = 0.443
- Strategy 2: (0.3 x 0.400) + (0.2 x 0.600) + (0.4 x 0.533) + (0.1 x 0.200) = 0.395
- Strategy 3: (0.3 x 0.667) + (0.2 x 0.467) + (0.4 x 0.267) + (0.1 x 0.400) = 0.411
- Strategy 4: (0.3 x 0.267) + (0.2 x 0.533) + (0.4 x 0.600) + (0.1 x 0.467) = 0.380

Finally, we can rank the strategies based on their closeness to the ideal solution and the furthest distance from the negative-ideal solution, as follows:

- Strategy 1: 0.443
- Strategy 3: 0.411
- Strategy 2: 0.395
- Strategy 4: 0.380

Therefore, based on the TOPSIS method, Strategy 1 is the best closed-loop SCM strategy (least focused on innovations), followed by Strategy 3 (most focused on costs, so economic criterion).

Numerical example – ELECTRE method

The next numerical example we want to present is one for the ELECTRE method. The ssumptions of the model are as follows:

- Criteria: Cost, Environmental impact, and Resource efficiency
- Alternatives: Alternative A, Alternative B, and Alternative C
- Cost: A has a cost of 500, B has a cost of 700, and C has a cost of 600
- Environmental impact: A has an impact score of 0.7, B has a score of 0.5, and C has a score of 0.6
- Resource efficiency: A has a score of 0.8, B has a score of 0.6, and C has a score of 0.7
- Weights: Cost has a weight of 0.4, Environmental impact has a weight of 0.3, and Resource efficiency has a weight of 0.3

Step 1: Normalize the criteria and alternatives To normalize the criteria, we use a linear scaling method to transform the values of each criterion to a common scale between 0 and 1. For example, for cost:

- A: 500/700 = 0.71
- B: 700/700 = 1
- C: 600/700 = 0.86

Similarly, we normalize the scores for environmental impact and resource efficiency for each alternative.

Step 2: Determine the concordance and discordance matrices The concordance matrix compares each pair of alternatives and assigns a value between 0 and 1 based on the degree of concordance (agreement) between them. We compare the normalized scores of each criterion for each pair of alternatives.

The discordance matrix compares each pair of alternatives and assigns a value between 0 and 1 based on the degree of discordance (disagreement) between them. We identify the largest difference between the scores of each criterion for each pair of alternatives.

Step 3: Calculate the net concordance and net discordance The net concordance and net discordance values for each alternative are calculated by summing the concordance and discordance values, respectively, for each pair of alternatives and weighting them by the importance of the criteria.

For example, for Alternative A, the net concordance value is calculated as follows: (0.71 x 0.3) + (0.7 x 0.3) + (0.8 x 0.3) = 0.745

The net discordance value is calculated as follows: max{(0.29 x 0.4), (0.5 x 0.3), (0.2 x 0.3)} = 0.12

Step 4: Calculate the outranking and global performance indices The outranking index for each alternative is calculated by subtracting the net discordance from the net concordance:

For example, for Alternative A: Outranking Index for A = Net Concordance for A - Net Discordance for A = 0.745 - 0.12 = 0.625

The global performance index for each alternative is calculated by normalizing the outranking indices for each alternative:

For example, for Alternative A: Global Performance Index for A = Outranking Index for A / sum of all Outranking Indices = 0.625 / (0.625 + 0.35 + 0.325) = 0.44

Similarly, we calculate the outranking and global performance indices for Alternatives B and C.

Based on the calculations, the ranking of the alternatives in order of importance for closed-loop SCM is:

1. Alternative A: Global Performance Index = 0.44
2. Alternative C: Global Performance Index = 0.32
3. Alternative B: Global Performance Index = 0.24

Therefore, Alternative A (lowest cost and resource efficiency) is the most suitable alternative for closed-loop SCM based on the given criteria and weights.

Numerical example – BWM method

Let’s assume we have identified the following four criteria for assessing the importance of closed-loop supply chain management: environmental impact, economic feasibility, stakeholder satisfaction, and technological feasibility. We also have five alternatives to consider: Option A, Option B, Option C, Option D, and Option E.

Step 1: Determine the weights of the criteria

We can use a pairwise comparison matrix to determine the weights of the criteria. Suppose the matrix is as follows (see Table 14).

Table 14. Pairwise comparison matrix to determine the weights of the criteria

Criteria	**Environmental Impact**	**Economic Feasibility**	**Stakeholder Satisfaction**	**Technological Feasibility**
Environmental Impact	1	3	5	3
Economic Feasibility	1/3	1	3	1
Stakeholder Satisfaction	1/5	1/3	1	1/3
Technological Feasibility	1/3	1	3	1

To calculate the weights, we first normalize the columns by dividing each element in the column by the sum of the elements in that column (see Table 15). Then we calculate the average of the normalized values for each row.

Table 15. Average of the normalized values for criteria

Criteria	**Environmental Impact**	**Economic Feasibility**	**Stakeholder Satisfaction**	**Technological Feasibility**	**Weight**
Environmental Impact	1	0.6	0.625	0.6	0.606
Economic Feasibility	0.333	1	0.625	0.2	0.539

Criteria	**Environmental Impact**	**Economic Feasibility**	**Stakeholder Satisfaction**	**Technological Feasibility**	**Weight**
Stakeholder Satisfaction	**0.2**	**0.333**	**1**	**0.2**	**0.417**
Technological Feasibility	0.333	1	0.625	0.2	0.539

Therefore, the weights of the criteria are as follows:

- Environmental Impact: 0.606
- Economic Feasibility: 0.539
- Stakeholder Satisfaction: 0.417
- Technological Feasibility: 0.539

Step 2: Determine the scores of the alternatives

We can use a pairwise comparison matrix to determine the scores of the alternatives for each criterion (see Table 16)

Table 16. The scores of the alternatives

Option	**Environmental Impact**	**Economic Feasibility**	**Stakeholder Satisfaction**	**Technological Feasibility**
A	3	4	2	3
B	2	3	4	2
C	4	2	3	3
D	2	4	2	3
E	4	3	3	4

To calculate the scores, we first multiply each element in the matrix by the weight of the corresponding criterion.

Then we calculate the sum of the weighted values for each row. The results are as follows:

Option A: 3 x 0.606 = 1.818 for Environmental Impact, 4 x 0.539 = 2.156 for Economic Feasibility, 2 x 0.417 = 0.834 for Stakeholder Satisfaction, and 3 x 0.539 = 1.617 for Technological Feasibility. Total score for Option A = 1.818 + 2.156 + 0.834 + 1.617 = 6.425

Option B: 2 x 0.606 = 1.212 for Environmental Impact, 3 x 0.539 = 1.617 for Economic Feasibility, 4 x 0.417 = 1.668 for Stakeholder Satisfaction, and 2 x 0.539 = 1.078 for Technological Feasibility. Total score for Option B = 1.212 + 1.617 + 1.668 + 1.078 = 5.575

Option C: 4 x 0.606 = 2.424 for Environmental Impact, 2 x 0.539 = 1.078 for Economic Feasibility, 3 x 0.417 = 1.251 for Stakeholder Satisfaction, and 3 x 0.539 = 1.617 for Technological Feasibility. Total score for Option C = 2.424 + 1.078 + 1.251 + 1.617 = 6.37

Option D: 2 x 0.606 = 1.212 for Environmental Impact, 4 x 0.539 = 2.156 for Economic Feasibility, 2 x 0.417 = 0.834 for Stakeholder Satisfaction, and 3 x 0.539 = 1.617 for Technological Feasibility. Total score for Option D = 1.212 + 2.156 + 0.834 + 1.617 = 5.819

Option E: 4 x 0.606 = 2.424 for Environmental Impact, 3 x 0.539 = 1.617 for Economic Feasibility, 3 x 0.417 = 1.251 for Stakeholder Satisfaction, and 4 x 0.539 = 2.156 for Technological Feasibility. Total score for Option E = 2.424 + 1.617 + 1.251 + 2.156 = 7.448

Therefore, based on the BWM method and the chosen criteria, Option E has the highest overall score of 7.448 and is the best alternative to implement for closed-loop supply chain management.

To sum up, different methods can produce different results, as they have different assumptions and criteria. Therefore, it is recommended to use multiple methods and compare their results to obtain a more robust and reliable decision. The convergence of results can provide confidence in the decision, while the divergence of results can highlight areas of disagreement and uncertainty that require further investigation or discussion.

Moreover, the choice of the best method should also consider practical considerations such as the availability of data, the complexity of the decision problem, the time and resources required, and the stakeholders' involvement and acceptance.

5-Discussion

The company in the case study has successfully integrated remanufacturing and waste management practices into its overall supply chain strategy, resulting in a reduction of waste generation, landfill disposal, and carbon emissions.

One of the key benefits of implementing closed-loop supply chain management practices is the reduction in production costs. By reusing components and materials through remanufacturing, the companies were able to reduce its raw material costs and lower the cost of producing new components. This is particularly important in the automotive industry, where raw materials and production costs can be high, and in food industry, where material lossess and producting byside products is high.

Another significant benefit of closed-loop supply chain management is the reduction of waste and landfill disposal. This not only reduces the environmental impact of the company's operations but also helps to preserve natural resources and minimize the need for new material extraction. The case study also highlights the importance of collaboration between companies. The company had to work closely with its suppliers to ensure that materials were designed for remanufacturing and recyclability, while also investing in specialized logistics equipment and optimizing transportation routes to reduce emissions.

Despite the benefits of closed-loop supply chain management practices, the case study also identified several challenges that companies may face in implementing these practices. The results suggest that companies that invest in these practices can achieve significant cost savings and environmental benefits while creating value for their customers and stakeholders.

As well, the MCDM methods can be used in supporting decision making in CLSCM. Numerical examples were provided to present the universal character of those methods in building circular economy through CLSCM, remanufacturing and wise waste management.

6-Conclusion

The case study results clearly demonstrate that closed-loop supply chain management practices by remanufacturing and waste management can offer significant benefits to companies in terms of cost savings, environmental sustainability, and stakeholder value creation. In the automotive and food industry, such practices can help reduce production costs, waste generation, and carbon emissions while promoting the circular economy.

The findings suggest that companies can benefit significantly from implementing closed-loop supply chain management practices by investing in remanufacturing and waste management programs. Therefore, while numerical examples are useful for illustrating the principles and techniques of MCDM methods, it is important to recognize their limitations and supplement them with real-world case studies and empirical research to ensure that MCDM methods are applied appropriately in practice.

One limitation of the study is that it focuses only on a two case studies for two chosen industries. Therefore, the generalizability of the findings to other industries or companies may be limited. Furthermore, the study did not assess the financial costs of implementing closed-loop supply chain management practices, which could be a significant consideration for some companies. Another limitation is using only numerical hypothetical examples in MCDM research is that it may not accurately reflect real-world decision-making scenarios. The use of hypothetical scenarios can simplify the decision-making process and overlook the complexity of actual decision-making situations.

Another limitation is that numerical examples do not necessarily capture the full range of factors that may be important in decision-making. For example, there may be social, cultural, or ethical considerations that are difficult to quantify and incorporate into a numerical analysis. Additionally, the use of numerical examples may not fully capture the preferences and opinions of stakeholders or decision-makers. Real-world decision-making often involves subjective judgments and negotiations among stakeholders, which may not be captured in numerical analyses.

Future research could focus on addressing the limitations of this study by conducting more case studies in different industries and regions. Furthermore, research could explore the financial implications of implementing closed-loop supply chain management practices to determine the return on investment for companies. Additionally, research could investigate the impact of government policies and regulations on the adoption of closed-loop supply chain management practices by companies.

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