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Navigating Complexities in Closed-Loop Supply Chains: A Review of Objectives, Uncertainties, and Decision Variables

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Abstract

The investigation of closed-loop supply chains (CLSC) and the principle of the circular economy (CE) becomes imperative in order to reduce the environmental impact associated with product development. This paper aims to conduct a literature review to explore and categorise the main content areas that are essential to the understanding of this research field and accordingly application of CLSC and the CE. To this end, this study focuses on identifying and analysing the forming factors in this context including the decision variables, measures of effectiveness, inherent uncertainties, and limitations associated with CLSC concepts. A significant contribution of this review lies in its detailed exploration of uncertainties associated with CLSC, highlighting their profound impact on achieving CE objectives. Through a comprehensive analysis of existing literature, the review identified and categorised the following uncertainties, and examined how they influence strategic decision-making and optimization process in CLSC. To the best of the authors' knowledge, such a review with critical analysis has not received its deserved attention in current literature. With the gained insights, this paper investigated the challenges and limitations associated with CLSC implementation in an uncertain environment. The discussion draws upon existing literature to highlight the hurdles that exist and propose potential methods to overcome them. A future road map is introduced by proposing a conceptual connection between circular supply chains (CSC) and inventory management, based on a structured analysis approach.

Keywords

Closed-Loop Supply Chain (CLSC); Circular Economy (CE); Supply Chain Management; Inventory Management; Optimization

1. Introduction

The transition from a linear economy to a CE presents an intricate tapestry of challenges and opportunities [1]. This pivotal shift is not only indicative of a move towards sustainable practices but is also a nod to the changing dynamics of modern supply chains [2]. In the given context, the notion of the CSC arises as a foundational structure that advocates for the principles of a CE—such as the repurchasing, refurbishment, and recycling of goods—in order to augment economic gains and facilitate sustainability. An additional development in this progression is the CLSC, which is a specific implementation of the CSC. In particular, CLSC ensure the optimal utilisation of resources by integrating the recovery and reintroduction of end-of-life products into the supply chain, thereby preventing waste[3]. This literature review delves deep into the world of CLSC and the broader canvas of the CE. Through a meticulous analysis of scholarly articles, this paper sheds light on the decision variables, objectives, challenges, uncertain factors, and limitations

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associated with CLSC. By integrating the findings from these valuable scholarly sources, this paper aims to offer a consolidated perspective on the current state of research in this domain and identify potential avenues for future exploration. The vast array of literature on CLSC presents varied perspectives, methodologies, and findings, leading to potential ambiguities. Introducing and answering these research questions aims to clarify and deepen the knowledge about the objectives, uncertain factors, and challenges that underpin the CLSC. The pertinent research questions include:

RQ1: How do the approaches and outcomes of single-objective versus multi-objective models in CLSC research reflect the complexities and trade-offs inherent in achieving sustainable and efficient supply chain management?

RQ2: Which uncertain factors predominantly influence CLSC models?

RQ3: What decision variables can be used in the CLSC?

RQ4: What are the primary limitations and challenges in the CLSC?

The functioning of CLSC is fundamentally governed by its objectives and decision variables. A clear understanding of these elements is crucial for industries aiming to transition from traditional to closed-loop systems. Decision variables in CLSC are classified into three categories: strategic (e.g., facility locations, capacities), tactical (e.g., resource allocations, supply planning), and operational (e.g., lot sizing, inventory management) [4]. Depending on the scope and focus, objectives within these studies may be categorized as either single or multiple-type. This classification aids in systematically analysing the characteristics and content of the reviewed literature, providing detailed insights in the subsequent sections of this review.

Uncertainties in any system can jeopardize its efficiency and output. It is an inherent and inevitable characteristic of a CLSC [5]. Uncertainties in CLSC poses significant challenges, potentially undermining system efficiency and output. These uncertainties can arise from various sources, including fluctuating market demands, the variable volume and quality of returned products, shifts in regulatory frameworks, and unforeseen supply chain disruptions [6, 7]. Recognizing these factors is pivotal for devising robust strategies that enhance resilience against such unpredictability. To improve the management and understanding of the uncertainty factors, it is important to categorise different types of uncertainty [5]. While the literature acknowledges the presence of these uncertainties, there is a noted deficiency in studies explicitly addressing t[8].

The primary motivation behind this review is to answer the pressing questions surrounding the objectives, challenges, and uncertain factors inherent in the CLSC framework. As industries globally grapple with the integration of forward and reverse logistics, understanding these intricacies becomes paramount. This review aims to not only synthesize existing knowledge but also to identify gaps and avenues for future research. The subsequent sections of the paper are organized as follows: a detailed background on the CE and CLSC, followed by the methodology adopted for this review, a discussion of the results, and finally, a conclusion summarizing the findings and providing insights for future endeavours.

2. Background

2.1 CSC and CLSC

The CE concept, deeply rooted in economics [1,2], industrial ecology [9, 10], and industrial symbiosis [11], has evolved significantly to emphasize closed-loop systems in response to environmental and socio-economic shifts [12,13]. This evolution has spurred the development ofCSC, designed to optimize sustainability and resource allocation through the principles of circularity [14,15]. CSCs, as analyzed by Batista et al. [16], merge sustainability aspects like reverse logistics [17], green supply chains [18], sustainable SCM (SSCM) [19], and CLSC [20], aiming to minimize environmental impact while promoting economic viability. CLSC, focusing on integrating forward and reverse logistics, have emerged as a sustainable business model, expanding the "produce-use-discard" paradigm into a cyclic one. Rao and Holt [21], and Rao [22] highlight the environmental and economic benefits of CLSC, which incorporates the recovery, refurbishment, and reintroduction of products [23]. The general CLSC illustrates in Figure 1. Initiated in the 1990s by pioneers like Thierry et al. [24] and Fleischmann et al. [25], the field has grown, as noted by Rubio et al. [26], to include key recovery options such as reuse, repair, remanufacturing, refurbishing, retrieval, and recycling [27], a concept further unified under "reconditioning" by Simpson [28]. CLSC faces challenges in managing the variability of returned product quality and quantity, reprocessing duration, and market demand for recovered goods [29, 30], underscoring the need for robust strategies to navigate these uncertainties. This comprehensive approach to CLSC, emphasizing sustainability and economic viability, sets the stage for exploring effective transitions to sustainable practices, addressing the intricate design and operation challenges within a genuinely CSC framework.

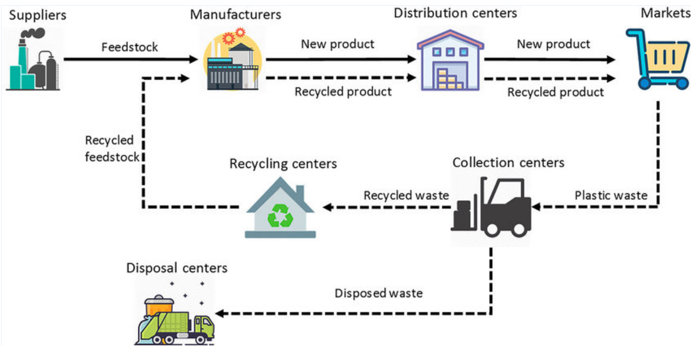

Figure 1. General form of CLSC [69]

3. Methodology

This review takes a distinct path by undertaking meta-analytic evaluations consistent with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines. PRISMA provides a structured outline to maintain methodological uniformity, ensuring thoroughness and clarity during the review process [32, 33].

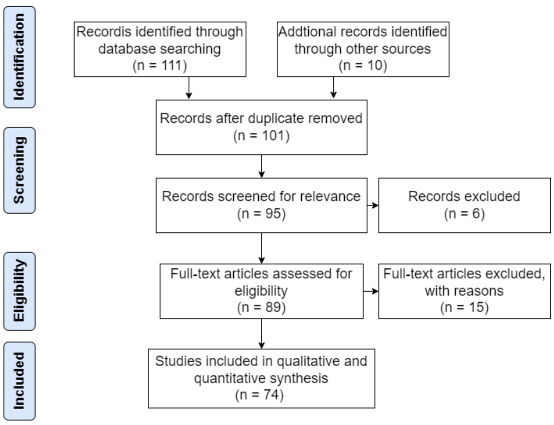

Figure 2: Literature review procedure based on PRISMA guidelines.

The discussion has been supported by the published paper and grey literature. Grey literature is information produced by organisations outside of the traditional commercial or academic publishing and distribution channels [36]. Although grey literature might showcase basic or preliminary conclusions, incorporating such sources is crucial to achieving the paper's aim, especially since many assessment tools for circularity originate from non-academic entities and corporate initiatives.

While individual search terms can scan electronic database fields, utilising a search syntax—a combination of terms interspersed with Boolean operators—is more potent. The primary operators used here include 'AND' and 'OR'. Researchers may use different words to describe the same concepts—especially across fields studying similar phenomena from different ideologies. This diversity of expression is essential to capture in a search, which is the reason synonyms for each of the concepts from the research question are used. To capture a concept's diverse expressions, especially across varying disciplines, synonyms are employed in the search, combined using the Boolean 'OR' operator. Search terms that represent different concepts are combined with AND. Figure 3, illustrates the interplay of 'OR' and 'AND' operators in a search.

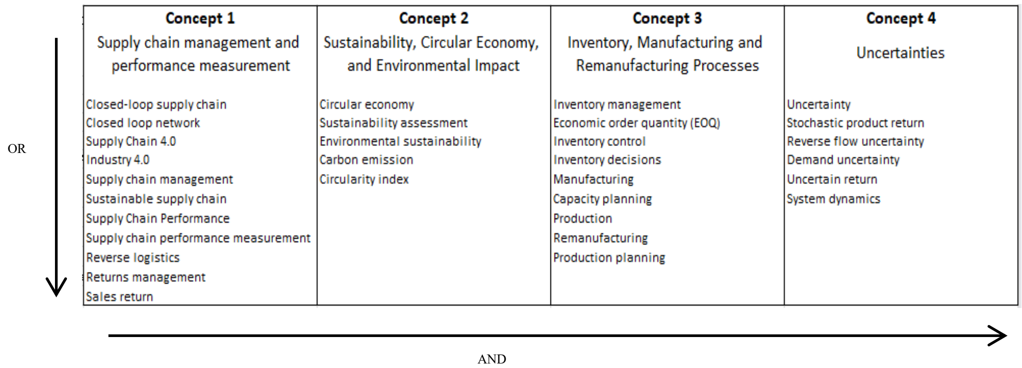

Figure 3: Schematic illustrating how search terms are combined with Boolean operators across the different concepts of research questions [34].

The search covered abstracts, titles, and keyword fields across databases including Web of Science, Scopus, ScienceDirect, Emerald, Wiley, and Google Scholar. Following this, a modified semi-structured snowballing technique [35] was employed to uncover more methodologies and indicators in reports and grey literature.

4. Result

4.1 Descriptive Outcomes of the Systematic Literature Assessment

Bibliometric evaluations focused on the temporal and geographical spread of CLSC-related papers, the nature of publications (peer-reviewed journals, grey literature, dissertations), and journal distribution.

For an initial insight into the topic's current landscape, a descriptive analysis was performed. This assessment, rooted in the structural attributes of the collected data, aimed to understand the research trajectory over time. Figure 4 depicts the temporal distribution of these publications.

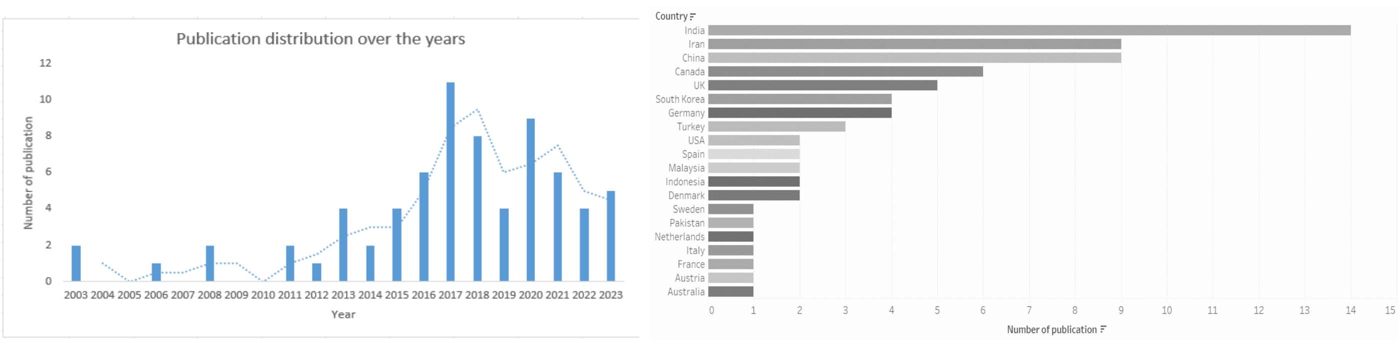

Figure 4: Publication distribution (left) and Global distribution (right) over the years.

The academic spotlight on CLSC research is traceable to the 1990s [37], [38]. The CLSC research trajectory exhibits three distinct phases over the 2003–2023 period: the "emergence" phase (2003–2012) with scant publications; the "transition" phase (2013–2016, 2021–2023) with modest growth; and the "acceleration" phase (2017–2020) marked by a surge in publications. This analysis emphasises the recent surge in interest, with a significant 59% of the 42 papers emerging between 2015 and 2020, underscoring the growing popularity of CLSC research. Figure 4 highlights the global distribution of CLSC research based on the first author's affiliation. Predominantly, countries such as India, China, Iran, Canada, the UK, Germany, and South Korea, along with several European nations, are the most active contributors to this field. Southeast Asia, notably Malaysia and Indonesia, also registers a budding interest in circularity assessment methods. Other regions (e.g., Latin America) are less expressive in terms of the number of articles assessed. These findings show the concern and interest of (mainly Asian and European) institutions and research bodies from different nations in developing comprehensive CLSC to assess and leverage this economic model shift.

4.2 Discussion on Objectives of CLSC

In a comprehensive exploration of the objectives associated with CLSC, an analysis was derived from a diverse collection of scholarly articles. This analysis categorizes the literature according to different objectives and modelling approaches employed in CLSC. Specifically, 'Multi-objective' models consider several objectives simultaneously, whereas 'Single-Objective' research focuses on a singular goal [39].

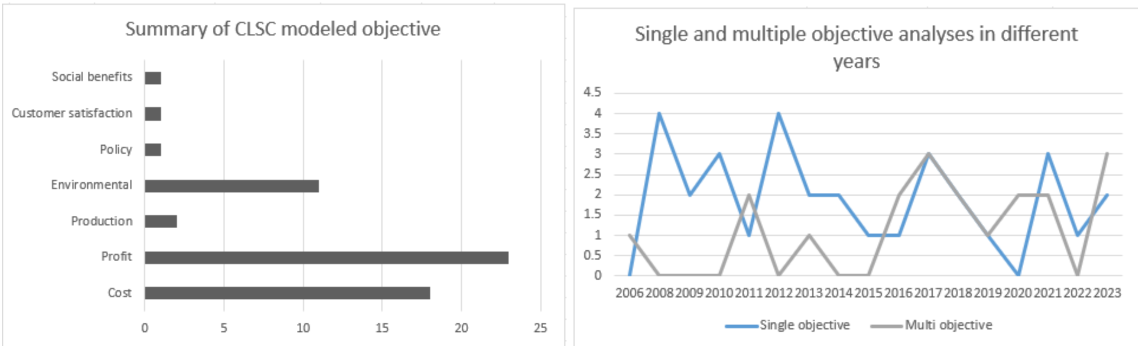

Figure 5: Summary of CLSC modelled objective (left) and Single and multiple objective analysis (right).

Figure 5 illustrates the trends in the utilization of single and multi-objective approaches over time. It has been observed that there is a declining number of studies adopting single-objective models in comparison to those employing multi-objective models. This shift indicates a growing recognition of the complexities in CLSC that require multiple objectives to be addressed concurrently. Moreover, the evident scarcity of multi-objective approaches in earlier studies highlights a significant gap in the research. This dominance of single-objective studies may be attributed to the traditional emphasis on isolating and optimising individual parameters for clarity and simplicity in research. In recent years, research in supply chains has been growing. These models capture the intertwined nature of objectives, such as cost, profit, and environmental considerations, offering a more holistic understanding of CLSC dynamics. Prioritising multi-objective modelling ensures a balanced approach, recognising that, in practice, trade-offs between objectives are inevitable and must be strategically managed [40]. After an in-depth analysis, it was discerned that cost- and profit-centric objectives emerge as a significant focus, followed closely by environmental considerations. While customer satisfaction, although crucial in practice, witnessed limited academic attention.

4.3 Discussion on Uncertain Factors of CLSC

Based on the reviewed literature, the authors of this article have classified the principal uncertainties within CLSC into ten categories: return rate, market demand, raw material supply, product price, total cost, social environment, pickup lead time, return yield rate, recycling quality, and recycling quantity, as illustrated in Figure 5. These categories are elaborated upon to guide future research. The literature review reveals that while many scholars have focused on a single uncertainty factor in their models, others have considered multiple uncertainties, thereby providing a more comprehensive analysis.

The uncertainty factors are classified accrording to the different CLSC forms, as illustrated in Figure 6. The analysis shows that market demand, return rate, and recycling quality together represent the majority of factors considered in single uncertainty studies. Models incorporating multiple uncertainties align more closely with real-world conditions. Notably, studies addressing both market demand and return rate constitute the largest proportion of research. CE ideology advocates for the implementation of practices that emphasize the reuse and recycling of products. This strategy has the potential to reduce the reliance on raw materials and decrease waste production, while potentially introducing variability in demand and return rate [41]. However, it is observed that not many in-depth studies exist on the other uncertainty factors. Accordingly, it is also necessary to conduct management research on these factors. From figure 7, it is observed that environmental uncertainty in CLSC primarily stems from integrating manufacturing, remanufacturing, and recycling activities, relying on parts recovered from returned products and procured from external vendors. Such integration is fraught with ambiguities surrounding the quantity, quality, and timing of returns [42]. These uncertainties influence the proportion of products recovered for diverse product recovery options, thereby affecting the processing and set-up costs across various facility centres.

Figure 6. Literature distribution of uncertainty factors (left) and Analysis of probabilistic models used for market demand uncertainty (right).

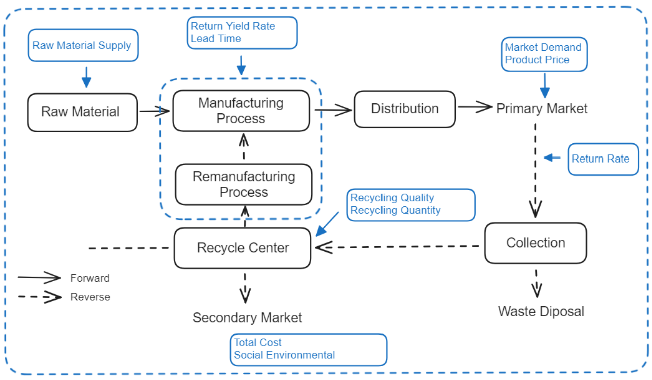

Figure 7. Classification of uncertainty factors across CLSC forms.

The integration of uncertainties into planning decisions requires an appropriate method for representing uncertain parameters, particularly focusing on market demand, which constitutes the largest proportion of research concerning uncertainty factors in CLSC. Figure 6 presents a comparative analysis of the frequency with which different probabilistic models are employed in scholarly articles, specifically focusing on modelling the uncertainty of market demand. Two primary methodologies identified are the scenario-based and the distribution-based approaches. From the data, it is evident that the Normal distribution is the most frequently applied. This preference can be attributed to the central limit theorem, which justifies the use of the Normal distribution under the assumption that the observed market demand is the sum of many small, independent effects [41]. The utility of the Normal distribution in CLSC analysis is further underscored by its ability to facilitate mathematical handling due to its symmetrical properties and the vast array of analytical tools available for this distribution. In the scenario-based approach, uncertainties are described through a set of discrete scenarios, each associated with a probability level that reflects the likelihood of that scenario's occurrence. For example, Cardoso, Barbosa-Póvoa, and Relvas [42] utilized three demand scenarios: optimistic, realistic, and pessimistic. scenario-based approach, though less frequently utilized, provides a framework for including multiple specific potential market conditions, which may be particularly useful when discrete market states are anticipated, such as in highly volatile markets or where strategic business decisions depend on specific market outcomes [43]. In terms of integrating these distributions with other uncertainty factors like return rates and recycling quality, the interdependencies must be acknowledged. For instance, market demand uncertainty can directly impact the return rates as consumer purchasing behaviour influences the volume and timing of returned products. Likewise, fluctuations in market demand can affect the quality and quantity of materials available for recycling, hence influencing the recycling quality. The analytical frameworks must, therefore, be capable of handling these interdependencies, likely requiring a hybrid approach that combines multiple distributions and scenario analyses to mirror the complex and dynamic nature of real-world CLSCs. Thus, the selection of appropriate distributions should be tailored to the specific characteristics of market demand and its interaction with other uncertainty factors in the supply chain.

4.4 Discussion on Decision Variables in CLSC

CLSC operates with the goal of integrating forward and reverse logistics seamlessly. Given this complexity, it is essential to categorise decision variables that allow for effective and efficient management of the CLSC. The proposed categorisation simplifies the intricate operations and strategies involved in CLSC by grouping decision variables that share a common focus or objective. Decision variables here meaning represent controllable choices available to a decision-maker [3]. The decision variables critical to the management of CLSC are strategically categorized to streamline the complex operations and strategies inherent to such systems. These variables, pivotal in controlling the dynamics of CLSC, are divided into three main categories as outlined by Chopra and Meindl [3]: strategic, tactical, and operational decision variables. These correspond to long-term, mid-term, and short-term decision-making, respectively. Figure 9 indicates the distribution of these decision variables across the papers reviewed, with a notable focus on the tactical variables, which account for 54% of all decision variables identified. Conversely, strategic decision variables are less frequently discussed in the selected studies.

Additionally, this paper further classifies the decision variables into six categories: Ordering and Inventory (e.g., lead times, order quantities), Manufacturing, Production, and Refurbishing (e.g., lot sizes, rates of manufacturing), Delivery and Transportation (e.g., shipment sizes), Finance(e.g., price of products), Human Resources, (e.g., workforce planning) Environment (e.g., mass of waste products). These categories encompassing various aspects of effective supply chain management. This classification aids in a deeper understanding of how decision variables interact within the framework of CLSC, thus facilitating more informed and strategic operational planning.

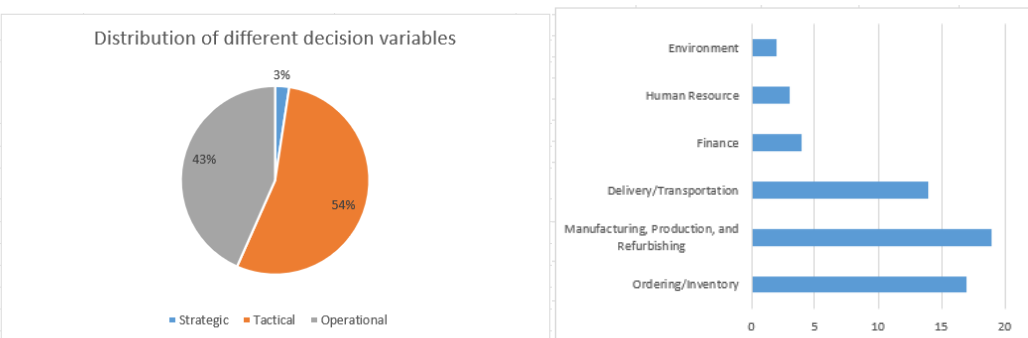

Figure 9:The distribution of different decision variables in the literature.

Inventory management and manufacturing are key topics in supply chain literature, reflecting their crucial roles in ensuring product availability and managing costs. The prominence of manufacturing and refurbishment in CLSC highlights their impact on product lifecycles and sustainability. Transportation is also significant in CLSC, optimizing costs and customer satisfaction through efficient delivery systems. Although financial strategies and human resources are less frequently discussed, their importance in economic feasibility and operational success is undeniable. Surprisingly, despite the global emphasis on eco-friendly practices, environmental sustainability receives minimal attention in CLSC literature.

The analysis indicates that while tactical and operational decision variables are well-covered in the literature, strategic decisions and certain critical aspects like environmental considerations and human resources management require more in-depth exploration. This could lead to a more holistic approach to CLSC management, ensuring not only efficiency and profitability but also sustainability and adaptability to changing market and environmental conditions. This observation suggests potential areas for future research, particularly in integrating strategic planning more profoundly into CLSC studies and addressing the underrepresented areas to provide a more balanced view of CLSC management.

4.5 Discussion on Limitations and Challenges in CLSC

The integration of CLSC and the CE is pivotal for meeting modern sustainability objectives. Current literature identifies key challenges and limitations, notably in modelling and methodology. The table illustrates the summary of categorized limitations and challenges in the CLSC literature paper is attached in the appendix. A review of esteemed journals highlights the prevalence of simplified models that often overlook complexities like multi-product setups and multi-echelon inventory systems, limiting their practical application in dynamic supply chain environments [44, 45]. Notably, the simplification in handling demand and return uncertainties, as well as other influential factors such as marketing and dynamic pricing, restricts these models' real-world applicability [46, 47]. These gaps are crucial in light of ongoing research aimed at developing a model that enhances supply chain circularity by accommodating production rates and inventory uncertainties in demand and returns. Future research is urged to incorporate more realistic factors and environmental impacts to develop robust, applicable models for sustainable supply chain management [48, 49]. This research aims to address these deficiencies by proposing a model that merges theoretical rigor with practical relevance, tailored to the complexities of modern supply chains.

5. Conclusion

The evolution of the CE and the CLSC signifies a momentous shift in the world of supply chain management. This paper offers a overview of the uncertain factors, objectives, decision variables, and limitations and challenges associated with CLSC. However, it's evident that the benefits, both economic and environmental, outweigh the challenges.

Firstly, while there's a considerable amount of research dedicated to CLSC and the CE, there exists a gap between theoretical robustness and practical applicability. Secondly, this paper documents that while academic research robustly explores various dimensions of CLSC, including the management of uncertainties, the practical integration of these factors remains an underexplored frontier. The evidence suggests that while models typically address single factors, real-world effectiveness demands a more holistic approach that considers multiple interrelated uncertainties simultaneously. In terms of decision variables, The intricate dynamics of decision-making in CLSC, from inventory management to manufacturing and environmental considerations, reveal the necessity for models that balance operational efficiency with strategic foresight. The discussion on objectives reflects a noteworthy trend towards multi-objective models, which contrasts with earlier research predominantly focused on single-objective approaches. This shift acknowledges the complexity of CLSC and the need for models that can simultaneously address multiple objectives. The growing recognition of these interconnected objectives in recent studies suggests a maturing of the field and a move towards more comprehensive and realistic models. Lastly, the examination of limitations and challenges in CLSC research not only highlights prevalent issues such as simplifications in modelling and the overlooking of dynamic real-world factors but also sets the stage for future investigations.

Appendix

Category	Challenges
Modeling and Methodology Limitations:	Single period model [50].
	Single product consideration [51].
	Assumed deterministic/stochastic properties [52].
	Assumed certain system dynamics or input types [53].
	Neglect of certain relevant parameters [54].
	Lack of efficient algorithms [55].
Real-world Applicability and Assumptions:	High degree of demand substitution [56].
	Non-consideration of real-world effects like marketing, pricing, etc [57].
	Simplifications like negligible manufacturing and remanufacturing times [58].
	Assumed certain transportation modes or costs [59].
Future Research Directions:	Integration of more real-world factors (e.g., demographic factors, drug characteristics) [60].
	Consideration of multiple products or entities (retailers, vendors) [61].
	Exploration of different modeling techniques or methodologies [62].
	Need to delve into solutions for managing closed-loop systems holistically [63].
	Consideration of green or environmental principles in modeling [64].
	Need for more comprehensive and holistic models for sustainable supply chain management [65].
Data and Uncertainty:	Need to consider uncertainties in parameters like demand, costs, prices [66].
	Challenges in predicting certain parameters [67].
	Challenges in handling large datasets or problem sizes [68].

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