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H2020 MSCA-ITN-2018

ReTraCE Project

Realising the **Tra**nsition towards the **C**ircular **E**conomy

Deliverable 1.6

Mathematical models for dealing with strategic decisions for designing circular supply chains: A review of the state-of-the-art and a methodological proposal

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie European Training Networks (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE).

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Part II:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie European Training Networks (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE).

List of acronyms

CE – Circular Economy

SC – Supply Chain

SCM – Supply Chain Management

GSCM - Green Supply Chain Management

SSCM - Sustainable Supply Chain Management

SSC - Sustainable Supply Chain

CSCs – Circular Supply Chains

CLSC – Closed Loop Supply Chain

RL - Reverse Logistics

BM - Business Models

WM - Waste Management

EoL – End of Life

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Part I[1]

Mathematical models for dealing with the strategic design of circular supply chains: A review of the state-of-the-art

[1] This study has also been published in the prestigious *Journal of Cleaner Production*, and is available online at this link.

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1. General purpose and objectives of the report

Over the past decade, significant attention has been devoted to Closed-Loop Supply Chain (CLSC) design problems. As such, this review aims at assessing whether the current modelling approaches for CLSC problems can support the transition towards a Circular Economy at a supply chain level. The paper comprehensively assesses the extent to which existing modelling approaches evaluate the performance of supply chains across the complete spectrum of sustainability dimensions. Also, the capability of the current approaches of incorporating strategic, tactical, and operational decisions is considered, along with adopted solution methodologies. As a result, a comprehensive analysis was performed on 254 selected articles. This paper emphasises how most of the current literature in the field is affected by a disconnection between supply chain design and the founding principles of Circular Economy. Specifically, the CLSC literature exhibits a reductionist interpretation of the Circular Economy. CLSC studies focusing on all three dimensions of sustainability are relatively rare, and performance measurement approaches appear to be very much focused on monetary issues. While methodological contributions appear adequate to focus on the non-deterministic nature of CLSC design problems, there is paucity of empirically-grounded research. Coherently, a research agenda is proposed, in order to address the mentioned gaps and increase the relevance of this research field to practice.

2. Background of the report

Traditionally, industrial societies have operated according to a make-use-dispose model, with end-of-life solutions for products mainly coinciding with landfilling and incineration (Andrews, 2015). Therefore, nowadays, providing novel consumption and production patterns is imperative if a transition towards a sustainable model of development needs to be accomplished (Rezaei and Kheirkhah, 2018).

Within this context, the notion of the Circular Economy (CE) has been receiving increasing attention (Ellen Macarthur Foundation, 2020). The Circular Economy is an alternative paradigm aimed at overcoming the existing 'take-make-dispose' production and consumption model, through a more effective use of resources, in order to accomplish a better balance among economy, environment, and society (Ghisellini et al., 2016); CE aims at promoting environmentally and socially sustainable industrial systems (Ellen MacArthur Foundation, 2013 and 2015 Miller Plc, 2013). According to the European Commission (2015), in a CE, the value of materials and products

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is maintained for as long as possible; waste and resource use are reduced, and resources are kept within the economy when a product has reached the end of its life, through reuse and recycle processes.

While governments and supra-national bodies are pushing the transition towards a CE through top-down legislation and directives, increased bottom-up efforts from industrial organisations are also essential (Bressanelli et al., 2019). As a result, the designing and planning of appropriate supply chains constitute a significant building block towards the implementation of CE practices (Genovese et al., 2017). At a supply chain (SC) level, different configurations can be adopted for implementing CE principles:

Reverse SC approaches, in which the focus is merely on the backward flow of products and materials, without any integration coordination with forward flow activities;

Open-loop SC approaches, that deal with both forward and reverse flows of products, with the third parties (other than original manufacturers) which are responsible for reverse operations (Genovese et al., 2017);

Closed-loop SC approaches, in which both forward and reverse networks are integrated within a centrally managed system (Rezapour et al., 2015).

Closed-Loop Supply Chains (CLSCs) can be said to have distinctive attributes when compared to traditional supply chains, thanks to the reprocessing of product flows and aftermarket recovery operations (Van Engeland et al., 2020). Organisations who decide to adopt CLSC approaches and reconfigure activities for CE practices may obtain environmental, social, and economic benefits. However, it must be noted that the adoption of CLSC configurations might be linked to large initial investments, due to the need of setting up dedicated facilities for collecting and reprocessing products at the end of their service life (Nagasawa et al., 2017); the design of CLSCs constitutes indeed a very significant strategic decision due to the long-lasting effects of such choices. As such, appropriate planning and design tools are required in order to cautiously assess the viability of CLSC configurations.

While CLSCs can be seen as the backbone of the implementation of CE principles at a micro- and meso-level, it must be remarked that the extant CLSC literature has been developed before the popularisation of the CE concept, with the design of CLSCs mainly driven by economic considerations related to product recovery (see, for instance, the seminal paper from Savaskan et al., 2004).

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To the best of authors' knowledge, there is no state-of-the-art review of the literature focusing on CLSC design problems, with an explicit focus on models, methods and the conceptualisation of sustainability dimensions. As a result, this paper performs a systematic literature review (SLR), aiming at assessing how the current CLSC design approaches can support the transition towards a CE at a supply chain level, through the evaluation of modelling assumptions and applications. The objective is to assess the integration of goals and assumptions of CLSC and CE thinking, and the capability of CLSC approaches to aid the transition towards a CE. Within this context, the ambition of this review is to clearly identify research gaps, in such a way to shed light on future research directions and provide some tangible guidelines which might be of use to researchers and practitioners involved in this field of study.

In order to answer the research questions and address the research objectives, the scientific literature was systematically reviewed, through the four-stage approach suggested by Maestrini et al. (2017). As a result, the body of literature was identified based on an initial search in SCOPUS using three sets of keywords; after a careful assessment, duplicate articles, review studies as well as papers which were not directly deal with CLSC design problems were excluded. Finally, the resulting sample of articles was carefully scrutinised and analysed, through the assessment of bibliometric data and a content analysis.

The remainder of the paper is organised as follows. A discussion of previous literature reviews on CLSCs is provided in Section 3, in order to illustrate the need for this further contribution. Section 4 elaborates on the methodology adopted for this research, providing special emphasis on the mechanisms for the selection and classification of the papers. Section 4 starts with a general bibliometric analysis of the selected papers; then, a detailed evaluation of the body of literature is provided, through a thorough content analysis. Section 5 provides a discussion of the emerging research gaps and recommendations for further research; finally, some conclusions are drawn in Section 6.

3. An Overview of Previous Literature Reviews on Closed-Loop Supply Chains and Reverse Logistics

In order to provide further clarity about the need for this study, this section provides an overview of all the review papers dealing with CLSCs. The full list of such literature reviews, along with their

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scope, is provided in Table 1. The classification of the papers is based on their main focus area; within each category, papers are then sorted in a chronological order.

The relationships between CLSCs and business models were first investigated by Wells and Seitz (2005). Meade et al. (2007) looked at the foundations, definitions and research opportunities within the Reverse Logistics (RL) field of study, which can be seen as closely related to CLSCs.

Rubio et al. (2008), analysed the potential of using mathematical models for solving challenges in RLs, developing a review of the literature from 1995 onwards. Also, Pokharel and Mutha (2009) discussed the increase in the interest in RL, with Ilgin and Gupta (2010) referring to environmental consciousness as the most important cause for this increase.

Atasu et al. (2008) developed a critical review of CLSC business models for product reuse inspired by industrial practice. They further classify the research into four streams (industrial engineering/operations research, design, strategy, and behavioural) and present a framework linking these streams. A follow-up study was provided by Guide and Van Wassenhove (2009). Akçcal and Çetinkaya (2011) analysed the quantitative literature on Inventory and Production Planning for CLSC systems. They broadly classify the work into deterministic and stochastic problems according to the modelling of demand and return processes. Furthermore, De Giovanni and Zaccour (2019) and Shekarian (2020) propose a selective survey of CLSC game-theoretic models.

Carrasco-Gallego et al. (2012) focused on reusable products, identifying peculiar business models and related CLSC configurations, basing their results on a set of real-world industrial case studies. San et al. (2012) and Diallo et al. (2017) performed similar efforts dealing with remanufacturing-focused CLSCs. Besides, Wei et al. (2015), and Jena and Sarmah (2016) focused on the specific process of product acquisition management for remanufacturing.

Souza (2013) classified CLSC problems in terms of strategic, tactical, and operational issues. He provided an overview of strategic and tactical decisions, also providing basic models for addressing such decisions. Among strategic decisions, a pivotal role is played by facility location issues, which were also reviewed, within CLSCs, by Melo et al. (2009). A framework to classify the various issues and parameters affecting strategic level decisions in RL has been developed by Sheriff et al. (2012). Furthermore, Schenkel et al. (2015) looked at value creation across CLSCs, suggesting promising research avenues for the operational and strategic levels.

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Table 1. Overview of previous literature reviews. (NP = Number of Papers reviewed)

Area	Paper	Year	NP	Main scope
CLSC	Atasu et al. (2008)	1995-2008	17	Business economics of product reuse
	Guide and Van Wassenhove (2009)	15 years	-	Closed-loop supply chains with a strong business perspective by focusing on profitable value recovery from returned products
	Akçcal and Çetinkaya (2011)	-	-	The state-of-art in quantitative models for inventory and production planning (I&PP) for CLSC systems
	Carrasco-Gallego et al. (2012)	Until 2010	10	A typology grounded on case studies
	San et al. (2012)	2001-2012	88	Closed loop supply chain with remanufacturing
	Souza (2013)	-	-	Strategic and tactical decisions
	Sahamie et al. (2013)	Until 2012	178	Applications to interdisciplinary and transdisciplinary industries
	Stindt and Sahamie (2014)	1984-2012	167	The main characteristics of CLSC planning in the process industry
	Wei et al. (2015)	Until 2014	87	Core (product) acquisition management for remanufacturing
	Jena and Sarmah (2016)	2000-2014	100	Remanufacturing and CLSC with special emphasis on acquisition management of returned items
	Cannella et al. (2016)	Until 2015	40	The inventory and order flow dynamics
	Glock (2017)	1980-2016	33	Decision support models for the management of closed-loop supply chains involving returnable transport items
	Diallo et al. (2017)	1985-2016	104	Quality, reliability, maintenance and warranty for recovered products and the remanufacturing activities
	Gaur and Mani (2018)	1992-2015	141	A conceptual framework, the major threats and opportunities for business firms engaged in a CLSC operation
	Coenen et al. (2018)	Until 2017	64	Understanding approaches to complexity and uncertainty in closed-loop supply chain management
	Braz et al. (2018)	2004-2018	56	Comparing the causes and mitigating factors of the bullwhip effect in forward supply chains and closed-loop supply chains.
	De Giovanni and Zaccour (2019)	2011-2018	73	Return functions and coordination mechanisms
	Shekarian (2020)	2004-2018	215	Factors influencing CLSC models based on the game theory (GT)

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	Meade et al. (2007)	1998-2006	45	An overview of definitions, current research, and future opportunities
	Rubio et al. (2008)	1995-2005	186	Main characteristics of articles on reverse logistics published in the production and operations management field
	Akçali et al. (2009)	Until 2008	22	Network Design for Reverse and Closed-Loop Supply Chains: An Annotated Bibliography of Models and Solution Approaches
	Pokharel and Mutha (2009)	Until 2008	164	Important features of reverse logistics such as product acquisition, pricing, collection of used products, RL network structure vis-à-vis the integration of manufacturing, and remanufacturing facilities of location of facilities for inspection and consolidation activity
	Ilgin and Gupta (2010)	1999-2009	540	Environmentally conscious manufacturing and product recovery (ECMPRO)
	Hazen (2011)	From 1998	35	Analysing academic reverse logistics disposition decision literature from a strategic perspective
	Hazen et al. (2012)	2000-2010	-	Identify the critical components of the reverse logistics (RL) disposition decision-making process
	Sheriff et al. (2012)	1998-2011	65	Develop a framework to classify the various issues/parameters affecting strategic level decisions in RL
RL & CLSC	Govindan et al. (2013)	1961-2012	234	Overview of contracts and a classification of coordination contracts and contracting literature in the form of classification schemes
	Tao and Yin (2014)	From 2000	-	Research methodology for reverse logistics network as a case study and quantity model analysis
	Aravendan and Panneerselvam (2014)	Until 2014	-	Network designs for the RL as well as CLSC
	Govindan et al. (2015)	2007-2013	382	The whole area in RL and CLSC
	Agrawal et al. (2015)	1996-2015	242	Adoption and implementation of RL practices; Forecasting product returns; Outsourcing; RL network from secondary market perspective; Disposition decisions
	Bazan et al. (2016)	1967-2015	183	Mathematical modelling of reverse logistics inventory models
	Govindan and Soleimani (2017)	Until 2014	83	A Journal of Cleaner Production (JCP) focus in the field of RL and CLSC
	Wang et al. (2017)	1992-2015	912	Main research themes, knowledge gaps, and future research opportunities
	Guo et al. (2017)	2006-2016	62	Supply chain contracts, with respect to supply chain structures and channel leaderships
	Larsen et al. (2018)	1995-2016	112	Identification of 15 distinct opportunities and 56 contingency factors for RSC-contribution, an interrelationship network between factors and the RSC's contribution.
	Islam and Huda (2018)	1999-2017	157	RL/CLSC in Waste Electrical and Electronic Equipment (WEEE)/E-waste
	Bensalem and Kin (2019)	1992-2017	631	A unidimensional and a multidimensional analysis on RL

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	Kazemi et al. (2019)	2000-2017	94	RL&CLSCM published in International Journal of Production of Research (IJPR)
	Jayasinghe et al. (2019)	2006-2017	65	Synergies between post-end-of-life of building (PEoLB) concepts and operations
SC & CE	Masi et al. (2017)	2005-2017	77	Supply Chain Configurations in the Circular Economy
	(Bressanelli et al., 2019)	-	63	Challenges in supply chain redesign for the Circular Economy
SCM & CE	De Angelis et al. (2018)	2001-2017	54	Supply chain management and the circular economy: towards the circular supply chain
BM & CLSC	Wells and Seitz (2005)	Until 2003	-	Typologies of the relationship between closed-loop supply chains and value-added business models
SCM & CLSC	Melo et al. (2009)	Last decade	120	Facility location models in the context of supply chain management
GSCM &RL& CLSC	Schenkel et al. (2015)	1998-2014	144	Value creation through the recovery of returned products
SSCM&GSCM&CLSC	Rajeev et al. (2017)	2000-2015	1068	A conceptual framework to classify various factors along the triple bottom line pillars of sustainability issues in the context of supply chains
SSC& CLSC	Manavalan and Jayakrishna (2019)	2009-2018	-	Various aspects of SCM, ERP, IoT and Industry 4.0; five perspectives of supply chain management namely Business, Technology, Sustainable Development, Collaboration and Management Strategy.
RL & WM& CLSC	Van Engeland et al. (2020)	1995-2017	207	Strategic network design using mathematical optimisation models in waste reverse supply chains
CLSC & CE	This study	2000-2019	254	Strategic network design models in CLSC to transition towards CE

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While Hazen (2011) emphasised the interdisciplinary and strategic nature of RL disposition decisions, and Hazen et al. (2012) identify the critical components of the RL disposition decision-making process, Sahamie et al. (2013) point out a need for transdisciplinary collaboration and talk about the major benefits of transdisciplinary research in CLSCs.

Govindan et al. (2013) and Guo et al. (2017) present an overview of supply chain contracts within CLSCs and Larsen *et al.* (2018) examine the contribution of RL to the firm's financial performance.

Tao and Yin (2014), Govindan et al. (2015), Agrawal et al. (2015), Wang et al. (2017), and Bensalem and Kin (2019) conduct general reviews regarding research methodologies for network design in the field of RL. The inventory and order flow dynamics in CLSCs have been analysed by Cannella et al. (2016) and Bazan et al. (2016). Moreover, decision support models for managing returnable transport items (RTIs) in CLSCs have been investigated by Glock (2017).

The Evolution of sustainability issues in supply chain management has been analysed by Rajeev et al. (2017), who looked at trends across industries and documented the rising interest towards CLSCs. Some reviews have focused upon various factors that affect the performance of sustainable supply chains like IoT (Manavalan and Jayakrishna, 2019) and the scope of value creation (Gaur and Mani, 2018); besides, Jayasinghe et al. (2019) explored the CLSC issues in the specific context of the construction industry, looking at the post-end-of-life of buildings.

At the meso-level, CLSCs face substantial challenges when it comes to implementation of the CE, as stated by (Masi et al., 2017). As such, De Angelis et al. (2018) discussed what CE principles mean in terms of supply chain challenges; Bressanelli et al. (2019) identified and categorise 24 challenges that may hinder the Supply Chain (SC) redesign for CE implementation.

The bullwhip effect, on the other hand, the propagation of uncertainty associated with the end customers' demand through the entire supply chain, has been widely discussed, in the context of CLSCs, in Braz et al. (2018). Also, knowledge gaps in terms of dynamic complexity and deep uncertainty in a transition towards CLSC management have been uncovered by Coenen et al. (2018).

The main limitations of the cited review papers are regarding the main focus of their exploration. Some merely investigate RL and CLSC studies published by specific and well-known Journals (Govindan & Soleimani, 2017; Kazemi et al., 2019); and some are reviews of specific industries, such as process industry (Stindt & Sahamie, 2014) and WEEE/E-waste (Islam & Huda, 2018).

In contrast to the previous more general reviews, three reviews provide overviews of strategic network design models for CLSCs: Akçali et al. (2009) provided an annotated bibliography of

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models and solution approaches for design problems for RL and CLSCs. Aravendan and Panneerselvam (2014) investigated mathematical models for RL network design; Van Engeland et al. (2020) gave an overview of strategic network design models for reverse supply chains for waste management.

The discussed reviews reveal that a lot of research has been performed in the fields of RL and CLSCs. However, while abundant streams of literature are also being produced about the Circular Economy paradigm and its applications, there is no study trying to assess, in an explicit manner, how the current modelling approaches for CLSC design can support the transition towards a CE, and to what extent CE-thinking is influencing the CLSC design literature. As such, a literature review of CLSC design approaches explicitly evaluating the alignment of this field of study with the CE agenda is now crucial in order to identify relevant research gaps, and to inform future avenues of investigation which might also contribute to industrial practice and policy-making objectives.

4. Research Method

As stated by (Denyer and Tranfield, 2009), a systematic literature review is useful for selecting, analysing and evaluating a particular body of knowledge which is relevant to a specific research question. This review was performed through the electronic database SCOPUS[2], which is considered as one of the main repositories of peer-reviewed journals articles. Furthermore, this database has been used extensively in producing systematic literature papers in the operations, logistics and supply chain management fields of study (Govindan et al., 2015; Jayasinghe et al., 2019; Jena and Sarmah, 2016). The review conducted based on four main steps proposed by Maestrini et al. (2017): source identification; source selection; source evaluation; data analysis. The four steps of the adopted research methodology are explained in detail in the following subsections.

4.1. Source Identification

In order to identify papers dealing with CLSC design problems, the following search terms were applied to the SCOPUS database:

- TITLE-ABS-KEY ("close* loop" AND "network* design*")
- TITLE ("close* loop supply chain*") AND TITLE-ABS-KEY ("network design*") OR TITLE-ABS-KEY ("network plan*") OR TITLE-ABS-KEY ("design model*")

[2] https://www.scopus.com

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- TITLE-ABS-KEY ("close* loop") AND TITLE-ABS-KEY ("supply chain*") AND TITLE-ABS-KEY (design)

The overview of the article search process is illustrated in Figure 1. The selection of very generic keywords allowed to source an initial set of 1165 relevant documents from SCOPUS. Limiting the search to English-language academic articles published in peer-reviewed journals, 766 documents were retained.

After a careful appraisal, duplicate articles, review studies as well as papers which were not directly concerned with CLSC design problems were excluded. As a result of this process, 254 papers were retained.

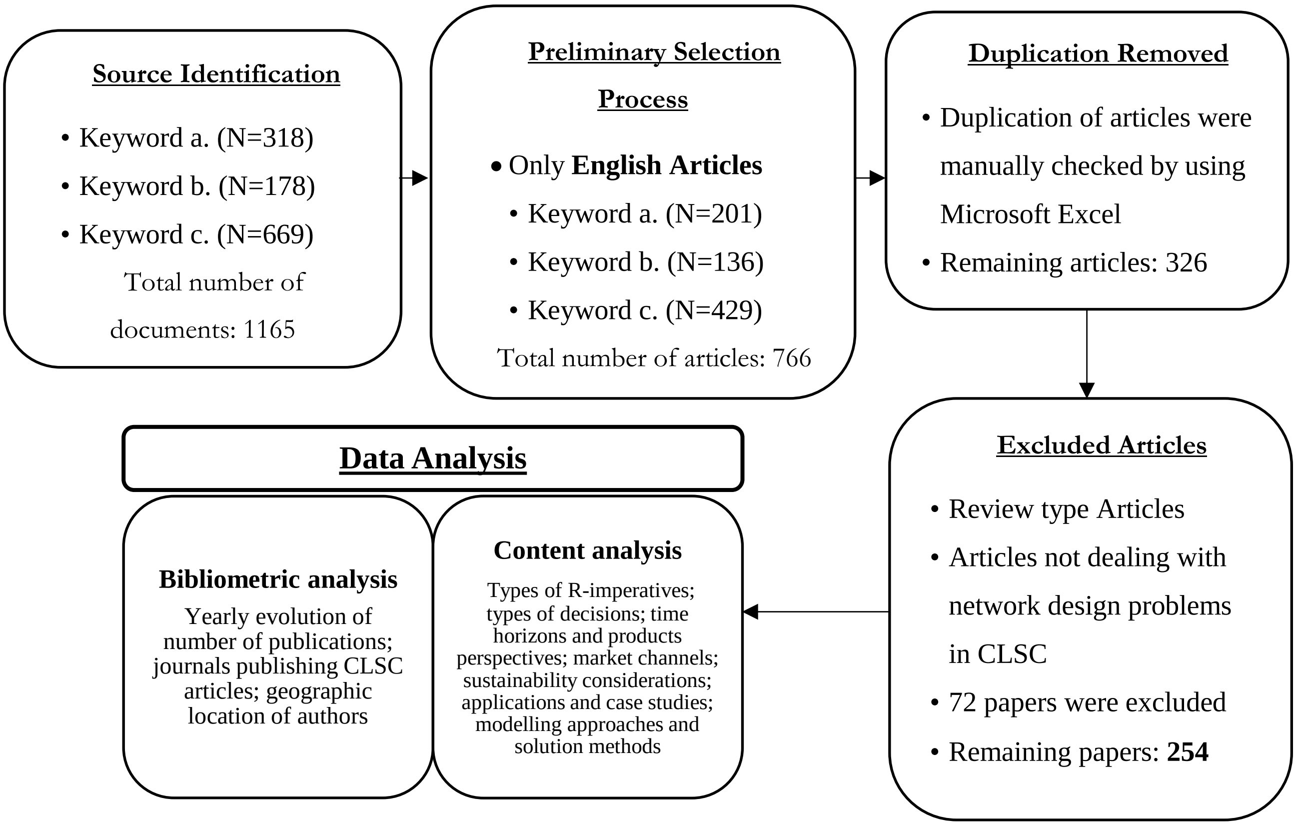

Figure 1. Article search and evaluation process

4.2. Source Selection

The next fundamental step after the retrieval of the relevant papers from the database was concerned with drawing the boundaries of the analysis. A cross-checking process was conducted manually using Microsoft Excel to eliminate duplicated results between three sets of keywords searching, excluding review articles (Akçali et al., 2009; Souza, 2013), which had been considered

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separately, and papers which are not relevant to CLSC planning; for instance, value-optimal sensor network design problem for steady-state and closed-loop systems (Zhang and Chmielewski, 2017) or local open- and closed-loop manipulation of multi-agent networks (Sahabandu et al., 2019) which are not concerning with supply chain issues and only appeared in search results as they have used "Closed-loop" or "Network design" in the title of their study. As a result, 254 papers were included in the subsequent analysis and thoroughly analysed.

4.3. Source Evaluation

The source evaluation entails the categorisation of the selected papers based on the key dimensions of analysis. The remaining 254 papers were further scrutinised according to their relevance to CLSC network design issues; thus, articles deemed to be irrelevant were excluded. This process ensures that all CLSC design articles were properly selected and reviewed in this study.

4.4. Data Analysis

The core and crucial objective of this review is to sum up the findings from the articles and to highlight the research gaps that need further attention from academics and specialists. In this phase, individual contributions are broken down into their constituent parts and their correlations to one another are established.

First, a bibliometric analysis was performed; this relied on a set of descriptive statistical techniques which provide an overview of the body of knowledge in a research field (Prévot et al. 2010). Data related to do CLSC design articles, such as academic journals publishing CLSC research, and countries where the research is taking place has been collected and analysed using Microsoft Excel (through. pivot tables, conditional formatting, and charts). Subsequently, a content analysis was performed, looking at key dimensions of CLSC design problems, such as: involved CE strategies (also known as R-imperatives); types of decisions supported by the models; time horizons and products perspectives; market channels; sustainability considerations; types of industrial applications and presence of real-world case studies; modelling approaches and solution methods, with a special emphasis on uncertainty-related dimensions.

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5. Bibliometric Data and Content Analysis

Results of the systematic literature review are presented in this section. The descriptive results of a general bibliometric analysis reported in the next sub-section are then followed by a comprehensive content analysis of the identified body of literature, specifically aimed at evaluating the alignment of current CLSC design approaches with the CE agenda.

5.1. General Bibliometric Analysis

Figure 2 shows the historical evolution of the number of publications obtained through the review protocol. Though there were no papers in 2002, 2005, 2006, and 2008, a rising interest in the CLSC design problems can be seen since 2012; approximately 91% of the papers were published from this year and later; this is clearly linked to the rising interest in cleaner production technologies and environmental impact mitigation which was also promoted through legislative initiatives.

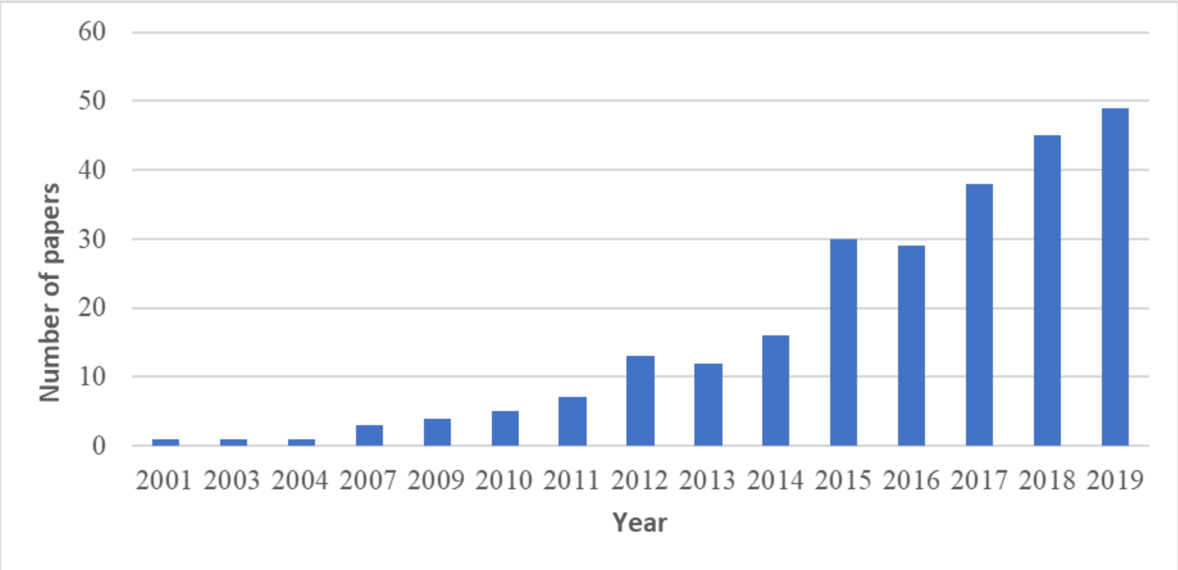

Figure 2. Number of publications across the period under investigation

Papers related to CLSC design are published in a total of 102 journals. 40 journals contain nearly 76% of the reviewed papers; the remaining are found in 62 journals, each with just one publication. A summary of the number of publications per journal is presented in Table 2 (the table includes only journals with five or more articles published). It can be seen that CLSC design models can be found not only in classical Operational Research (OR) and Industrial Engineering journals, but

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also in publications which have a very distinct environmental focus (such as Journal of Cleaner Production). 132 articles can be retrieved in various journals with fewer publications (4 or less) in this field; these are grouped under the label "others". The complete list of entries in this category is shown in Table A1 in the Appendix; notable journals in this category include Omega, Annals of Operations Research, Expert Systems with Applications, Transportation Science, thus reinforcing the relevance of CLSC design problems for the Management Science and OR discipline.

Table 2. Journals publishing CLSC articles (# = Number of Publications)

Journal	**#**
Journal of Cleaner Production	26
International Journal of Production Research	16
Computers and Industrial Engineering	13
International Journal of Production Economics	10
Computers and Chemical Engineering	8
International Journal of Advanced Manufacturing Technology	8
European Journal of Operational Research	7
International Journal of Logistics Systems and Management	6
Transportation Research Part E: Logistics and Transportation Review	6
Applied Mathematical Modelling	6
Sustainability (Switzerland)	5
Applied Soft Computing Journal	5
Other Journals (4 papers and below)	132
Total	**254**

The **geographic location** of the authors was also analysed. Figure 3 demonstrates that about 64% of the total papers are from Asian countries like Iran and China, which are the ones that are contributing the most to the topic of CLSC design. The reason for the importance of this subject among Iranian scholars is not only due to environmental concerns, but it has an economic origin. The closed nature of the Iranian economy (due to sanctions and limitations on international trade) has placed a strong emphasis on remanufacturing and repairing activities, providing a strong rationale for promoting closed-loop supply chains (Vargas-Sánchez, 2020). As regards China, the rising concern about CLSC development in China is influenced by the recent adoption of the Circular Economy as a strategic priority in both the latest 5-year plan and in a dedicated EU-China Memorandum of Understanding (Mathews & Tan, 2016). For the aforementioned reasons, state entities have increased budgets for the promotion of CLSCs in industrial practice, through several schemes and incentives. Surprisingly, no case studies addressing CLSC design were found in African countries from the review.

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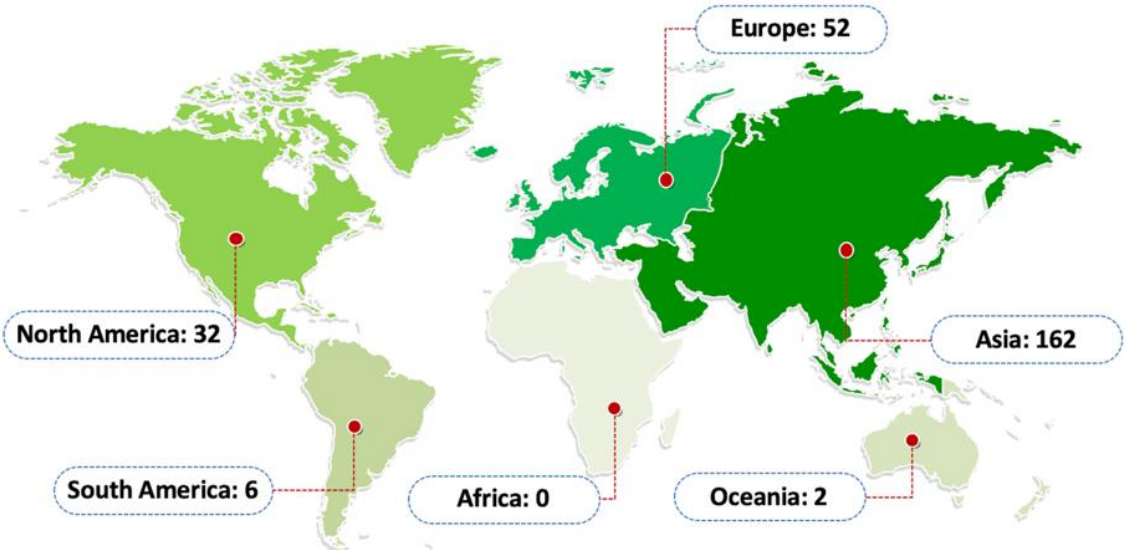

Figure 3. Geographic locations of the corresponding author

After the bibliometric analysis provided in this sub-section, papers have been analysed in detail, in order to evaluate their modelling approaches in terms of the proposed treatment policies, types of decisions tackled, market channels analysed, sustainability indicators involved. As such, the main objective of the next sub-sections is understanding the alignment of the CLSC design literature with the current Circular Economy agenda.

5.2. R-imperatives

The reprocessing strategies (also known as **R-imperatives**) used in CLSCs determine what types of returned products can be dealt with, largely affecting the configuration of the network. As already stated above, the previous reviews in the CLSCs and RL field identified four types of reverse flows: recycling, remanufacturing, repair, and reuse (see Section 3). However, the careful scrutiny of the identified body of literature revealed a wider array of treatment policies which are incorporated in CLSC design models, namely: Reselling, Reusing, Reconditioning, Recovering, Repairing, Refurbishing, Remanufacturing, Dismantling, Recycling, Shredding, along with other recovery options which are investigated by a very small number of studies, such as Donating, Refining and Retreating. In the following, all the identified pathways are discussed in detail along with their frequency of occurrence in the examined body of literature (represented by n), starting from the less destructive procedure and ending with the most destructive ones. Besides, Table 3 presents the different industrial sectors where such R-imperatives were deployed, along with their frequencies.

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First of all, the products that are not compatible with markets can be **donated** (n=1) to NGOs which also is a way to earn tax credits from the government (Darbari et al., 2019). **Reselling** (n=14) is another option which entails selling the used products to the secondary markets in an as-is condition at a lower value (Hazen et al., 2012). **Reuse** (n=29) refers to the usage of a product, component, or material over and over again with the purpose of re-employing it without the necessity of repair or refurbishment (Macarthur, 2020). In **reconditioning** (n=3), a product undergoes a full cleaning process and is renovated to its original condition without any significant upgrade (i.e., substitution of components) (Gaur et al., 2017). Some products can be reused after chemical processing in **refinery** (n=1) centres (Dehghan et al., 2018), or through **retreating** (n=1) ((Lu et al., 2019). **Repairing** (n=49) relates to the treatment of very minor defects in an object, with the objective of replacing faulty components and restoring its original functionality (Nasr et al., 2018); such process generally happens through ad-hoc non-standardised operations. In a **refurbishing** (n=21) process, a product is restored to its original condition (J. Gaur et al., 2017); such process involves the modification of an product with the aim of restoring its initial technical standards and functionalities. **Remanufacturing** (n=117) denotes a highly standardised industrial process in which cores are restored to the original as-new or even enhanced condition and functioning (Nasr et al., 2018); product-specific remanufacturing practices can be identified, such as tire re-treading (Pedram et al., 2017). The **recovery** (n=51) process can be dealt with by the original manufacturer of the product or by a third-party, and would encompass different levels of expertise depending on the product types (Das and Chowdhury, 2012).

If the quality of returned products is not adequate, they will be transported to disassemblers to be **dismantled** (n=43) (E. Özceylan et al., 2014); products are broken into pieces and components, to be sent for further processing. **Recycling** (n=136) was among the early recovery options to be modelled; it refers generally to the relevant operations which involve the reprocessing of waste for the purpose of extracting valuable raw materials (Nasr et al., 2018). **Shredding** (n=3) involves a capital intensive mechanical process aimed at recovering metals from end-of-life vehicles, also producing auto-shredder residues (ASR), a combination of materials such as plastics, textiles, and glass (GHK and Bio Intelligence Service, 2006).

Different facilities, as well as technology, will be required in CLSCs depending on the various treatment strategies. For instance, inspection and reselling of returned products will be happening at dedicated quality control and redistribution centres. On the other hand, recycling and remanufacturing, which are the most popular recovery options in CLSC models, deal with material

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and components and are more technology-based. Hence distinctive facilities, like recycling and remanufacturing centres, need to be established and therefore require more capital investment (Srivastava, 2008). However, other recovery options such as repairing and refurbishing are more skill-based and therefore require higher investments in labour.

Table 3 summarises all the presented R-imperatives, along with the frequency with which they appear in the literature and related industrial applications.

While “Reduce” practices, which are trying to limit the reliance of industries on virgin raw materials revising production and consumption patterns, are undoubtedly the main strategy in a CE framework, there is no emphasis on “Reducing” practices in CLSC literature, as can be seen from derived categorisation. This is due to the fact that most of the CLSC literature still supports a “perennial growth” view which might be incompatible with a proper CE (Genovese and Pansera, 2020). It appears that most of the modelling approaches are proposing design configurations which tend to close the loop of existing forward supply chains, rather than designing new production units which are fully inspired by a CE paradigm.

A general CLSC structure is given in Figure 4, showing the recovery options are derived from the literature review (See Table 1). CLSCs involve both forward and reverse flows in which the products return to the market after the applicable recovery options. Forward flows involve suppliers, manufacturers, distributors, primary customers and disposal centres; reverse flows allow products to be recovered and re-processed through collection and inspection centres. These facilities need to be linked with each other in order to satisfy customer demand.

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Table 3. Review of various treatment policies in CLSC (NP = Number of Publications)

Treatment	NP	Products
Donating	1	**Laptop** (Darbari et al., 2019)
Reselling	14	**Faucet**(Gholipoor et al., 2019)**; Laptop** (Darbari et al., 2019); **Inkjet printers**(Govindan et al., 2017); **Mobile phone**(Ahmadi & Amin, 2019); **Electronic products**(Subramanian et al., 2013); **Vehicles**(Mora et al., 2014); **Glass**(Baptista et al., 2019).
Reusing	29	**Dairy** (Yavari and Geraeli, 2019)**; Laptop** (Darbari et al., 2019); **Inkjet printers**(Govindan et al., 2017); **Consumer goods** (Zeballos et al., 2018); **Copier industry** (Nagasawa et al., 2017); **Glass** (Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Maria Isabel Gomes Salema et al., 2010); **Vehicles**(Mora et al., 2014); **Mushroom**(Banasik et al., 2017); **Home appliance** (Chen et al., 2015; Faccio et al., 2011)**; Edible oil**(Dehghan et al., 2019)
Reconditioning	3	**Battery**(Gaur et al., 2017)**.**
Refining	1	**Edible oil** (Dehghan et al., 2018)
Retreating	1	**Electronic products** (Lu et al., 2019)
Recovering	51	**Glass**(Devika et al., 2014; Morteza Ghomi-Avili et al., 2019; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Jabbarzadeh et al., 2018; Pourjavad & Mayorga, 2019a; Maria Isabel Gomes Salema et al., 2010; Zeballos et al., 2012); **Oil and gas**(Montagna & Cafaro, 2019; Saedinia et al., 2019); **Paper**(A.R. Ahranjani et al., 2018); **Consumer goods**(M.A. Kalaitzidou et al., 2015; L.J. Zeballos et al., 2018); **Tire**(Ebrahimi, 2018; Subulan et al., 2015); **Household appliance**(Faccio et al., 2011; Ghorabaee et al., 2017); **Medical device** (Hasani et al., 2015); **Electronics industry**(Polo et al., 2019); **Battery**(Mota et al., 2015; Tosarkani & Amin, 2019); **Mushroom**(Banasik et al., 2017); **Iron and steel**(Vahdani and Mohammadi, 2015);
Repairing	49	**Laptop**(A. Hamidieh et al., 2018); **Gold**(Mostafa Zohal & Soleimani, 2016); **Consumer goods** (Kalaitzidou et al., 2015); **Hospital furniture** (H. Soleimani & Kannan, 2015); **Geyser**(Garg et al., 2015); **Tire**(Pedram et al., 2017); **Plastic water cane** (H. Soleimani et al., 2016); **Copier industry**(Harold Krikke, 2011); **Vehicles**(Cruz-Rivera & Ertel, 2009); **Polyethylene tanks**(Shamsi et al., 2019)**; Battery**(Langarudi et al., 2019)**; Plastic**(Xu et al., 2017)**; Refrigerator**(Krikke et al., 2003)
Refurbishing	21	**Hospital furniture**(Surya Prakash et al., 2017)**; Copier industry** (Harold Krikke, 2011); **Vehicles** (Cruz-Rivera and Ertel, 2009).
Remanufacturing	117	**Wire and cable**(Ehsan Mardan et al., 2019); **Dairy**(Yavari & Geraeli, 2019; Yavari & Zaker, 2019); **Glass**(Baptista et al., 2019; Devika et al., 2014; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Pourjavad & Mayorga, 2019a); **Food Industry** (Abdi et al., 2019); **Consumer goods**(M.A. Kalaitzidou et al., 2015; L.J. Zeballos et al., 2018); **Electrical and Electronical Equipment**(S. H. S. H. Amin & Baki, 2017); **Copier Industry** (Cilacı Tombuş et al., 2017; Fleischmann et al., 2001; Harold Krikke, 2011; Keisuke Nagasawa et al., 2017; Steinke & Fischer, 2016; Talaei et al., 2016); **Gold**(Mostafa Zohal & Soleimani, 2016); **Construction machinery**(Yi et al., 2016); **Consumer goods**(M. A. M. A. Kalaitzidou et al., 2015); **Iron and steel**(Behnam Vahdani, 2015; Behnam Vahdani & Mohammadi, 2015); **Cell phone** (Khatami et al., 2015); **Tire** (Amin et al., 2017; Pedram et al., 2017; Subulan, Taşan, & Baykasoğlu, 2015); **Automotive spare parts**(Rezapour et al., 2015); **Hospital Furniture**(H. Soleimani & Kannan, 2015); **Paper**(Fleischmann et al., 2001; Pazhani et al., 2013); **Automotive** (Rezapour et al., 2015; Üster et al., 2007); **Plastic water cane**(H. Soleimani et al., 2016); **Furniture**(Accorsi et al., 2015);**Bread**(Mirakhorli, 2014); **Refrigerator**(H. Krikke et al., 2003; Y. Wang et al., 2012); **Vehicles**(Cruz-Rivera & Ertel, 2009; Mora et al., 2014); **Information and communications technology (ICT) industry**(Behnam Vahdani & Ahmadzadeh, 2019)**; CFL light bulbs**(Taleizadeh et al., 2019); **Multimedia company**(Z. H. Zhang et al., 2019); **Electronic components**(Mota et al., 2018); **Plastic**(Xu et al., 2017); **LCD and LED TVs**(Zhalechian et al., 2016); **Iron and Steel**(Behnam Vahdani & Mohammadi, 2015); **Home appliance** (Chen et al., 2015); **Bottles** (Lee, Jeong-Eun ; Lee, 2011)**; Refrigerator**(Krikke et al., 2003); **Tire** (Pedram et al., 2017; Subulan et al. 2015).

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Dismantling	43	**Laptop**(Darbari et al., 2019); **Automotive**(Eren Özceylan et al., 2017); **Inkjet printers**(Govindan et al., 2017); **Electronic products**(Lu et al., 2019); **Vehicles**(Cruz-Rivera & Ertel, 2009; Mora et al., 2014); **Notebook**(Mohajeri & Fallah, 2016); **Information and communications technology (ICT) industry**(Behnam Vahdani & Ahmadzadeh, 2019)**; Geyser** (Garg et al., 2015).
Recycling	136	**Faucet**(Gholipoor et al., 2019)**; Glass**(Devika et al., 2014; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Pourjavad & Mayorga, 2019a; Luis J. Zeballos et al., 2012); **Oil and gas**(Saedinia et al., 2019)**; Laptop**(Darbari et al., 2019; A. Hamidieh et al., 2018); **Food Industry** (Abdi et al., 2019); **Paper**(A. Rahmani Ahranjani et al., 2018; Fleischmann et al., 2001; Pazhani et al., 2013; Safaei et al., 2017; M.I.G. Salema et al., 2009); **Edible oil**(Dehghan et al., 2018, 2019); **Tire** (S. H. Amin et al., 2017; Ebrahimi, 2018; A. M. A. M. Fathollahi-Fard et al., 2018; Kannan et al., 2009; Pedram et al., 2017; K. Subulan, Taşan, & Baykasoğlu, 2015); **Filter**(Morteza Ghomi-Avili et al., 2018); **Consumer goods**(M. A. M. A. Kalaitzidou et al., 2015; L. J. L. J. Zeballos et al., 2018); **Electronic products**(Lu et al., 2019; L. Ma & Liu, 2017; Subramanian et al., 2013); **Automotive**(Eren Özceylan et al., 2017); **Inkjet printers**(Govindan et al., 2017); **Copier industry**(Fleischmann et al., 2001; Harold Krikke, 2011; K. Nagasawa et al., 2017); **Gold**(Mostafa Zohal & Soleimani, 2016); **Construction machinery**(Yi et al., 2016); **Battery** (Fallah et al., 2015; Fazli-Khalaf et al., 2019; Langarudi et al., 2019; P. Sasikumar & Haq, 2011; Shen, 2019; Sherif et al., 2019; K. Subulan, Taşan, & Baykasołlu, 2015; Kemal Subulan et al., 2015); **Iron and steel**(B. Vahdani et al., 2013; Behnam Vahdani, 2015); **Hospital Furniture**(H. Soleimani & Kannan, 2015); **Geyser**(Garg et al., 2015); **Household appliance**(W. Chen et al., 2015; Keshavarz Ghorabaee et al., 2017); **Plastic water cans** (H. Soleimani et al., 2016);**Furniture**(Accorsi et al., 2015); **Vehicles** (Cruz-Rivera & Ertel, 2009; Mora et al., 2014); **Refrigerators** (H. Krikke et al., 2003; Y. Wang et al., 2012); **Steel**(Sahebi et al., 2019); **Mobile phone**(Ahmadi & Amin, 2019); **Bottled water**(Papen & Amin, 2019); **CFL light bulbs**(Taleizadeh et al., 2019); **Polyethylene tanks**(Shamsi et al., 2019); **Plastic**(Kannan et al., 2009; Ren et al., 2020; Xu et al., 2017; Yousefi-Babadi et al., 2017); **Mushroom**(Banasik et al., 2017).
Shredding	3	**Automotive** (Eren Özceylan et al., 2017); **Vehicles**(Cruz-Rivera and Ertel, 2009; Mora et al., 2014)

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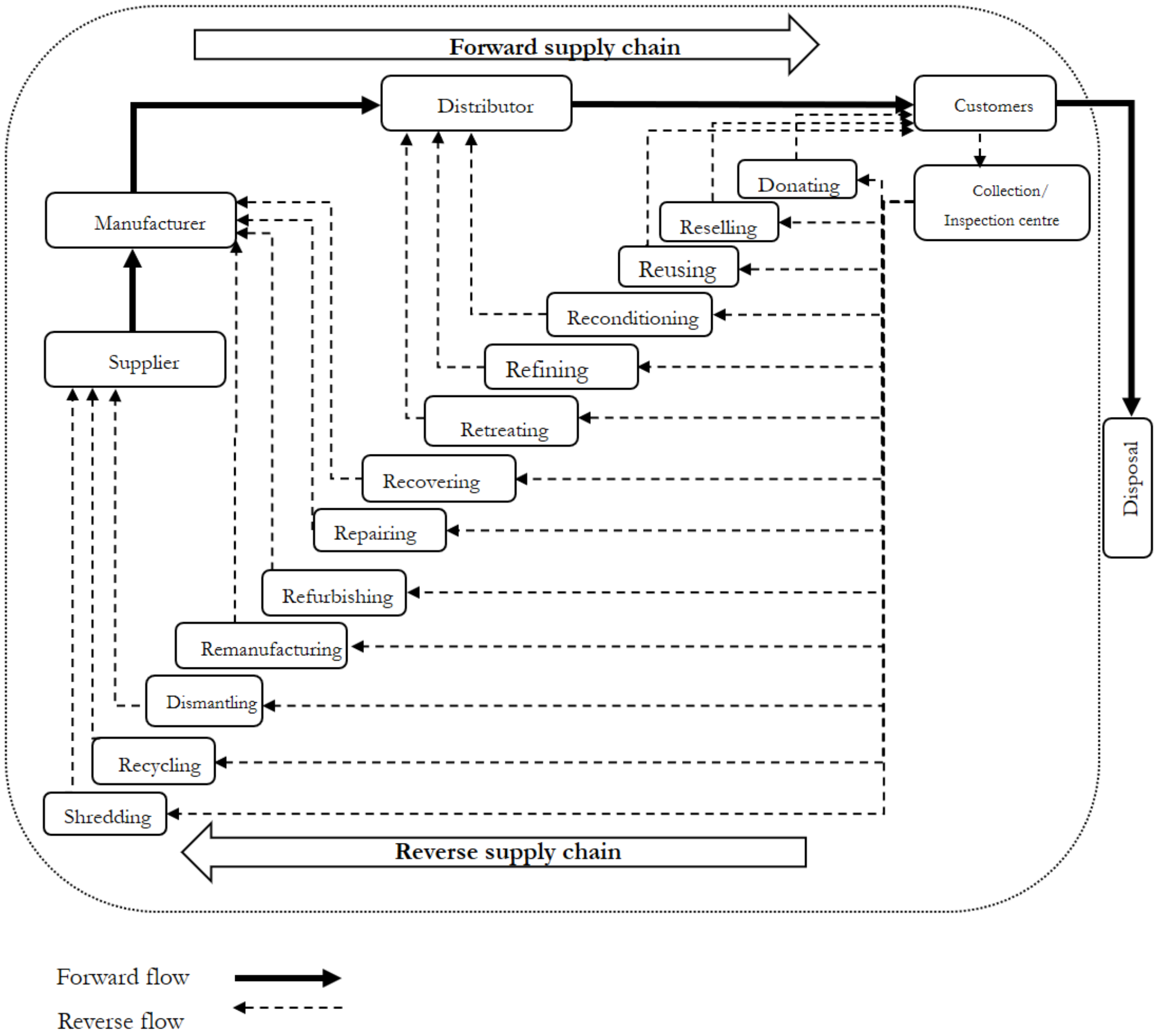

Figure 4. General layout of a closed-loop supply chain

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5.3. Decision-Making

When it comes to types of decisions involved in the considered CLSC models, 74 of the surveyed papers are addressing the CLSC design problem from a merely strategic point of view (see Table 4). These are based on long-term arrangements and mainly characterised by binary decision variables specifying opening or closing a facility in a particular location, performing capacity expansions at a specific time, determining an appropriate transportation mode or installing a certain technology along with material and product flows among them (A. Çalık et al., 2018).

The second group, related to tactical decisions, denotes mid-term choices; it is observed that tactical decisions are very well integrated with strategic ones. Such integration is indeed proposed addressing by more than 50% of the reviewed articles (N=149). Tactical decision variables could be binary as in the case of allocation decisions, supplier selection, planning activities (procurement, production/reproduction, distribution/redistribution; storage and distribution planning). Also, integer variables can be involved in the case of transportation flows (the quantity of items - products, raw material, etc. - to be shipped among the network entities), inventory levels, price levels of products, fleet composition and allocation issues.

Operational decisions involve detailed vehicle routing plans along with production and disassembly schedules (concerned with a daily/weekly horizon). Since the keyword "Design" has been included in all of our queries to identify sources of dataset for establishing this literature review, no paper is just concerned with Operational issues (N=0). Furthermore, there are just two contributions incorporating short-term operational decisions into long and/or medium-run ones (Rezaei and Kheirkhah, 2018; Sasikumar et al., 2017).

In a nutshell, most CLSC models (149 articles) are trying to integrate strategic and tactical decisions to avoid sub-optimal solutions produced by a disjointed design of forward and reverse elements in CLSCs. While some articles (N=22) are attempting to address the integration of all the three decisions levels (Ramezani and Kimiagari, 2016; Steinke and Fischer, 2016), this is generally characterised by a remarkable complexity level.

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Table 4. Types and examples of decision levels

Decision Level	Decision Type	Examples
Strategic decisions (N=74)	Number of Facilities	(Alireza Hamidieh & Fazli-Khalaf, 2017; Özkir & Başligil, 2012; S. Prakash et al., 2017)
	Facility location	(Ghadge et al., 2016; Lee, Jeong-Eun ; Lee, 2011; Mota et al., 2015)
	Facility capacity	(Y.-W. Chen et al., 2017; Ghassemi et al., 2018; Zhen, Huang, et al., 2019)
	Facility scale	(M. Liu et al., 2019; Montagna & Cafaro, 2019; Zhen, Sun, et al., 2019)
	Technology type	(Farrokh et al., 2018; Sadeghi Rad & Nahavandi, 2018; K. Subulan, Taşan, & Baykasoğlu, 2015)
	Transportation channels	(A. Rahmani Ahranjani et al., 2018; Atabaki et al., 2019; Mostafa Zohal & Soleimani, 2016)
	Product design	(Das & Chowdhury, 2012; H. Krikke et al., 2003; L.J. Zeballos et al., 2018)
	Transportation mode	(Amalnick & Saffar, 2017; Forouzanfar et al., 2016; Pei & Li, 2018)
Tactical decisions (N=7)	Allocations	(S.A. Darestani & Pourasadollah, 2019; Yavari & Geraeli, 2019; Zhao et al., 2018)
	Supplier selection	(Fard et al., 2017; Nobari & Kheirkhah, 2018; Sahebjamnia et al., 2018)
	Inventory levels	(Ahmet Çalık et al., 2017; Morteza Ghomi-Avili et al., 2019; E. Mardan et al., 2019)
	Pricing decisions	(Kaya & Urek, 2016; Litvinchev et al., 2014; Taleizadeh et al., 2019)
	Discount level	(Soroush Avakh Darestani & Hemmati, 2019; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Majid Ramezani et al., 2014)
	Transportation amount	(M.B. Fakhrzad & Goodarzian, 2019; Farrokh et al., 2018; Y. Yang et al., 2017)
	Planning activities	(Fernandes et al., 2010; M.I.G. Salema et al., 2009; Luis J. Zeballos et al., 2016)
	Vehicle selection	(A. Çalık et al., 2018; Ming Liu et al., 2018; RajKumar & Satheesh Kumar, 2015)
	Fleet composition	(A.R. Ahranjani et al., 2018; Garg et al., 2015)
Strategic/ Tactical decisions (N=149)	Facility location/allocation	(Ghahremani-Nahr et al., 2019; Yadegari et al., 2019; Zhao et al., 2018)
	Facility location/ Inventory Management	(Soleimani et al., 2016; Li et al., 2018; Abdallah et al., 2012)
	Facility location/ Product flow	(Chen et al., 2015; Saffar et al., 2014; Salema et al., 2010)
	Number of facilities/ Supplier selection	(Kalaitzidou et al., 2015; Fallah-Tafti et al., 2014; Dehghan et al., 2019)
	Transportation mode/ Transportation quantity	(Amalnick et al., 2017; Subulan et al., 2015a; Haddadsisakht and Ryan, 2018)
Strategic/ Operational decisions (N=1)	Facility location/ Transportation Scheduling	(Rezaei and Kheirkhah, 2018)

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Tactical/ Operational decisions (N=1)	Transportation quantity/ Reorder point	(Sasikumar et al., 2017)
Strategic/ Tactical/ Operational decisions (N=22)	Facility location/ Inventory level/ Vehicle Routing Planning	(Zhalechian et al., 2016;
	Facility location/ Allocations/ Flowshop scheduling	(Yousefi-Babadi et al., 2017)
	Facility location/ Allocations/ Vehicle Routing Planning	(Ebrahimi., 2018; Masoudipour et al., 2019; Sherif et al., 2019)
	Facility location/ Transportation and Inventory decisions/ Production planning	(Steinke and Fischer., 2016; Ghomi-Avili et al., 2019)

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5.4. Time horizons and products perspectives

Considered models can also be classified on the basis of the time horizon they adopt. Single-period models are static and reflect decisions that are taken only once, mainly at a beginning of a time horizon (Haddadsisakht & Ryan, 2018; Kadambala et al., 2017; Zhen, Huang, et al., 2019); multi-period models are dynamic and optimise on the whole time horizon (Ghassemi et al., 2018; D. Yang et al., 2019). Approximately 46% of the models comprised in this review are based on multi-period approaches (Kalaitzidou et al., 2015; Özceylan et al., 2017; Pishvaee and Torabi, 2010). It is noteworthy that 72% of multi-period CLSC models incorporate strategic as well as tactical/operational decisions. Multi-period models appear to be naturally suited to represent design problems characterised by multiple decision levels across a given time horizon.

Regarding product varieties, most of the earlier studies (Atabaki et al., 2019; Farrokh et al., 2018; Tsao et al., 2017) and nearly 47% of the reviewed articles are concerned with single product models. However, multi-product models have gained more attraction in recent years and investigated by 53% of studies (Mardan et al., 2019; Sahebjamnia et al., 2018; Zeballos et al., 2018). The interest towards multi-product models is coherent with the need to acquire a view of CLSCs inspired by industrial symbiosis mechanisms, where supply chains of different products can collaboratively exchange flows of materials. The yearly evolution of CLSC models in terms of products and periods arrangements are shown in Figure 5.

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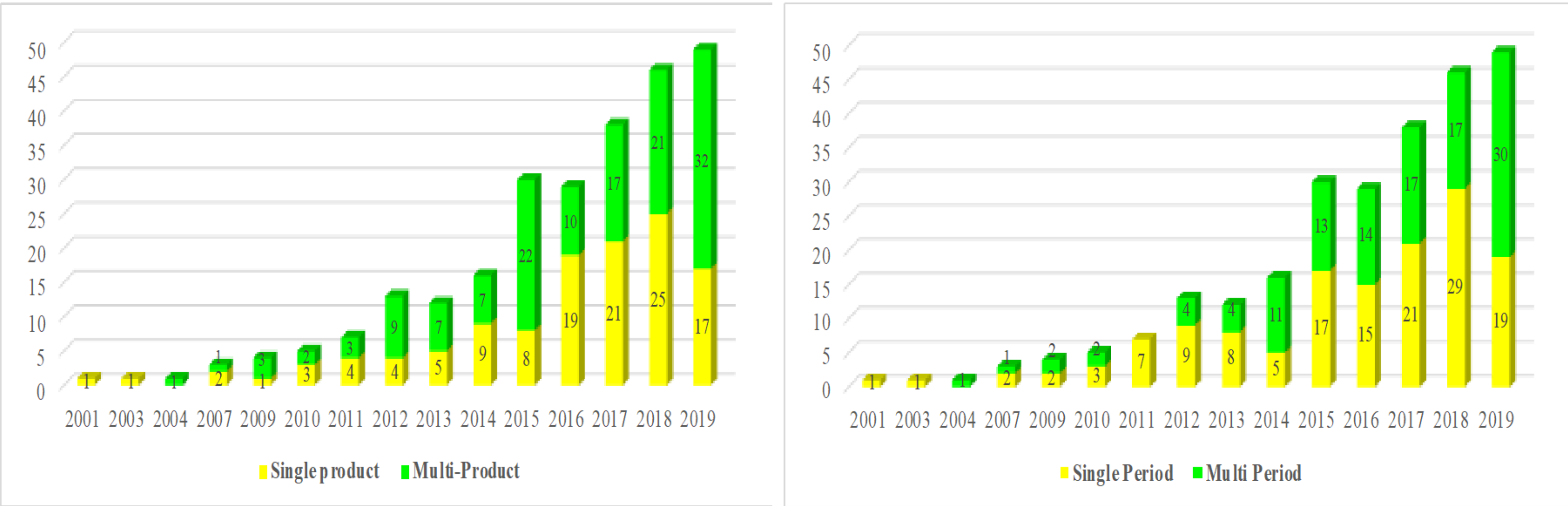

Figure 5. Analysis of products and periods in the surveyed mathematical modelling approaches

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5.5. Market channels

CLSC design models have been adapted to various business scenarios and market structures, including B2B (Business-to-Business) and B2C (Business-to-consumer) contexts. Within B2C applications, the perspective of secondary markets is also considered while designing CLSCs, through the evaluation of the potential activation of specific distribution channels. Alumur *et al.* (2012) investigated the significance of secondary market flows, and their capability of generating revenues for companies. Multiple market channels can offer an opportunity especially in countries where secondary markets are characterised by high demand. However, marketing products through secondary channels can be more complicated than selling new ones (Agrawal et al., 2015). Just a minority of papers (59) provide an explicit representation of secondary markets in CLSCs; also, no paper considers more articulated channel structures (e.g., tertiary or multiple market levels). The majority of the considered papers (77%) just deal with primary market distribution channels. This indicates that, in practice, goods are most likely to be discarded only after one or two utilisations. This might be due to implicit assumptions about lower demand levels from secondary market channels.

5.6. Sustainability Dimensions and Objective Functions

Sustainability dimensions include economic, environmental and social factors; as such, the design of sustainable CLSCs should be conducted according to all the pillars of sustainability. An effective CLSC should contribute, in a positive way, to all three dimensions of sustainability (Korhonen et al., 2018). In this sub-section, the mathematical models from the considered sample have been scrutinised, in order to understand to what extent economic, environmental and social criteria are included in objective functions and constraints.

The review reveals that *green* CLSC design, including economic and environmental criteria, has been widely studied (Amalnick and Saffar, 2017; Fakhrzad and Goodarzian, 2019; Ghomi-Avili et al., 2018; Tiwari et al., 2016; Zohal and Soleimani, 2016), while there has been less attention for social criteria. Figure 6 demonstrates the distribution of the reviewed papers regarding the three dimensions of sustainability; this figure also shows the yearly evolution of the consideration for the three pillars of sustainability in the CLSC literature. It can be noticed that the economic objective is always present in the whole set of studies, apart from just one article which is only assessing the environmental dimension of sustainability. Out of the 254 papers, 95 explicitly include environmental criteria, and 76 out of the 254 papers address the problem considering two of the

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three dimensions of sustainability (Dubey et al., 2015; Hajiaghaei-Keshteli and Fathollahi Fard, 2019; Mirmohammadi and Sahraeian, 2018).

Meanwhile, papers considering social criteria seem rare. From 2013 onwards, several authors started studying the social dimension of sustainability simultaneously with the other two dimensions. To be more specific, only 36 papers in total make an effort to include social indicators in their mathematical formulation (Azadeh et al., 2016; Fazli-Khalaf and Hamidieh, 2017; Mirakhorli, 2014); there is no paper simultaneously optimising social and environmental dimensions without considering the economic one.

The adoption of environmental as well as social sustainability indicators for measuring the performance of CLSCs has been recognised as a crucial area that requires a systematic study (Bubicz et al., 2019). This study has also reviewed the most common indicators associated with each dimension.

Three main indicators seem to be associated with the economic dimension: measures related to minimisation of the total cost is used in 170 papers; the maximisation of the net profit appears in 79 papers. The maximisation of time responsiveness of the supply chain is covered in 13 papers; risk-based measures appear in 11 studies. Net present value (NPV) is adopted by 6 publications, quality-based indicators by 5 authors. Flexibility-based indicators appear in only 3 papers. Generally, cost minimisation and profit maximisation indicators are independent of multiple and single-period features of the problem under study. Meanwhile, NPV can be employed when an assessment over multiple periods is considered (Moreno-Camacho et al., 2019). As illustrated in Figure 7 (top chart), cost-based dimensions are the most common economic indicators, appearing in 170 papers.

The minimisation of environmental emissions (including CO_2-eq and Greenhouse Gas (GHG) emissions caused by supply chain activities) represents the most popular environmental objective, included in 55 studies as shown in Figure 7 (centre chart). Generic indicators dealing with minimisation of environmental impacts are covered by 15 papers (Pourjavad and Mayorga, 2019b; Rajak et al., 2018). Waste generation (Wang et al., 2012, 2013) as well as energy consumption (Kadambala et al., 2017; Pazhani et al., 2013; Wang et al., 2012) are mentioned in 6 studies each. Carbon policies (Gao & Ryan, 2014; Mohammed et al., 2017; Mohammed et al., 2018), namely referring to Carbon Taxes, appear in 5 studies. Target collection rates, defect rates, greenness

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indicators, disposal rate and last but not least Life Cycle Analysis measures are less commonly employed. In the light of the transition to a circular economy, measuring the circularity degree of a CLSC is crucial. However, interestingly, no study included such a CE-inspired measure in the objective function or constraints of the developed mathematical models. No paper was found including an indicator of the *circularity degree* of the supply chain in the mathematical formulation; this remains a significant gap which needs to be addressed in future research.

According to the reviewed body of literature, the first paper to consider social objectives was published by Özkir and Başligil, (2013). In this sub-domain, the total number of jobs created is the most frequent social indicator, as it is employed in 16 papers (Figure 7, bottom chart). Customer satisfaction is a basic component in all organisations due to fierce market competition (MahmoumGonbadi et al., 2019); also, customers have a crucial role in the transition to the CE; it is not surprising that customer-centric indicators are covered by 10 papers. Other indicators in the same sub-dimension include social responsibility measures, such as the total working time lost due to injuries (Hajiaghaei-Keshteli and Fard, 2019; Samadi et al., 2018), as an indicator of employee wellbeing and of the technological appropriateness of the supply chain (Moreno-Camacho et al., 2019). Also, some papers consider training hours for employees and community service hours (Darbari et al., 2019).

CLSCs have this potential to help industries achieve the transition to more sustainable production methods. However, the current literature reveals that a true consideration of circularity is missing in current CLSC design models; also, the social dimension is overlooked. It can be said, therefore, that a reductionist approach towards sustainability measurement is currently dominant in the CLSC design literature.

Table 5. Objective functions

Objectives	Single Objective	Bi-Objective	Multi-Objective (more than two objectives)
No of Articles	130	69	55

The above-mentioned reductionist approach can be also retrieved analysing the types of objective functions employed in the considered models (Table 5). Regarding single objective models, the most common objective among shortlisted papers is to minimise the total supply chain cost; 83 out of 130 articles are only dealing with cost issues (Sherafati and Bashiri, 2016; Torabi et al., 2016);

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the remaining ones are mainly related to maximising net profits (Atabaki et al., 2019; H. Ma & Li, 2018).

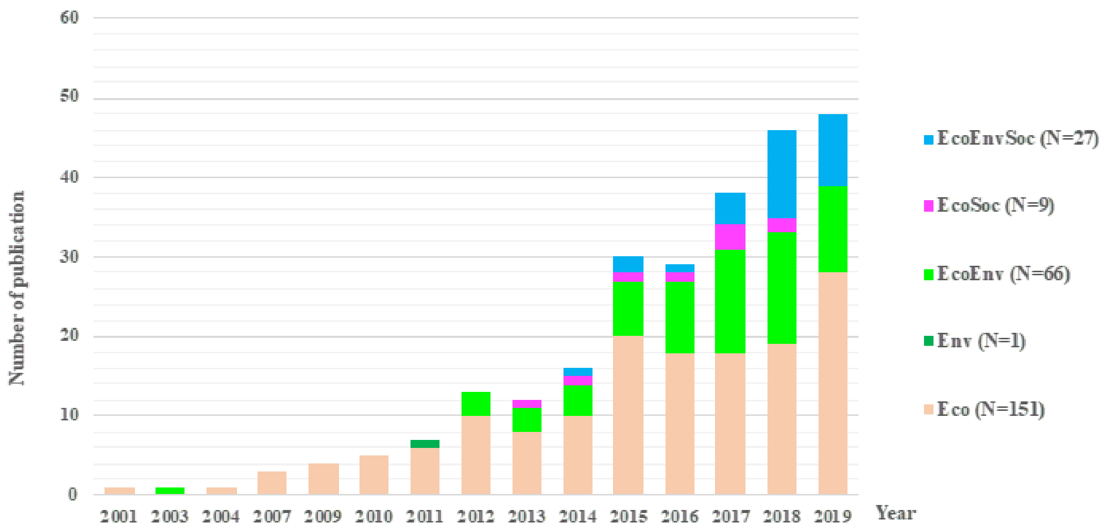

Figure 6. Focus on TBL sustainability dimensions and yearly evolution

The most significant objectives to be combined with cost minimisation and profit maximisation in bi-objective models were related to the minimisation of environmental emissions like CO_2-eq (Tornese et al., 2018; Zhao et al., 2018), delivery tardiness (Mirakhorli, 2014; Pishvaee & Torabi, 2010), maximisation of social impacts (A. M. Fathollahi-Fard et al., 2018) and responsiveness of the network (Dubey et al., 2015; A. Hamidieh et al., 2018). Environmental objectives started to be considered in CLSC literature starting from the seminal work of Krikke et al. (2003). Even though 55 CLSC models are multi-objective, only 23 of them are integrating the three dimensions of sustainability in their objectives; as such, this reinforces the view that the literature appears to be adopting a reductionist approach to the evaluation of sustainability (Gasparatos et al., 2009). Details related to objectives and the yearly evolution of objective functions to be optimised are found in **Error! Reference source not found.**.

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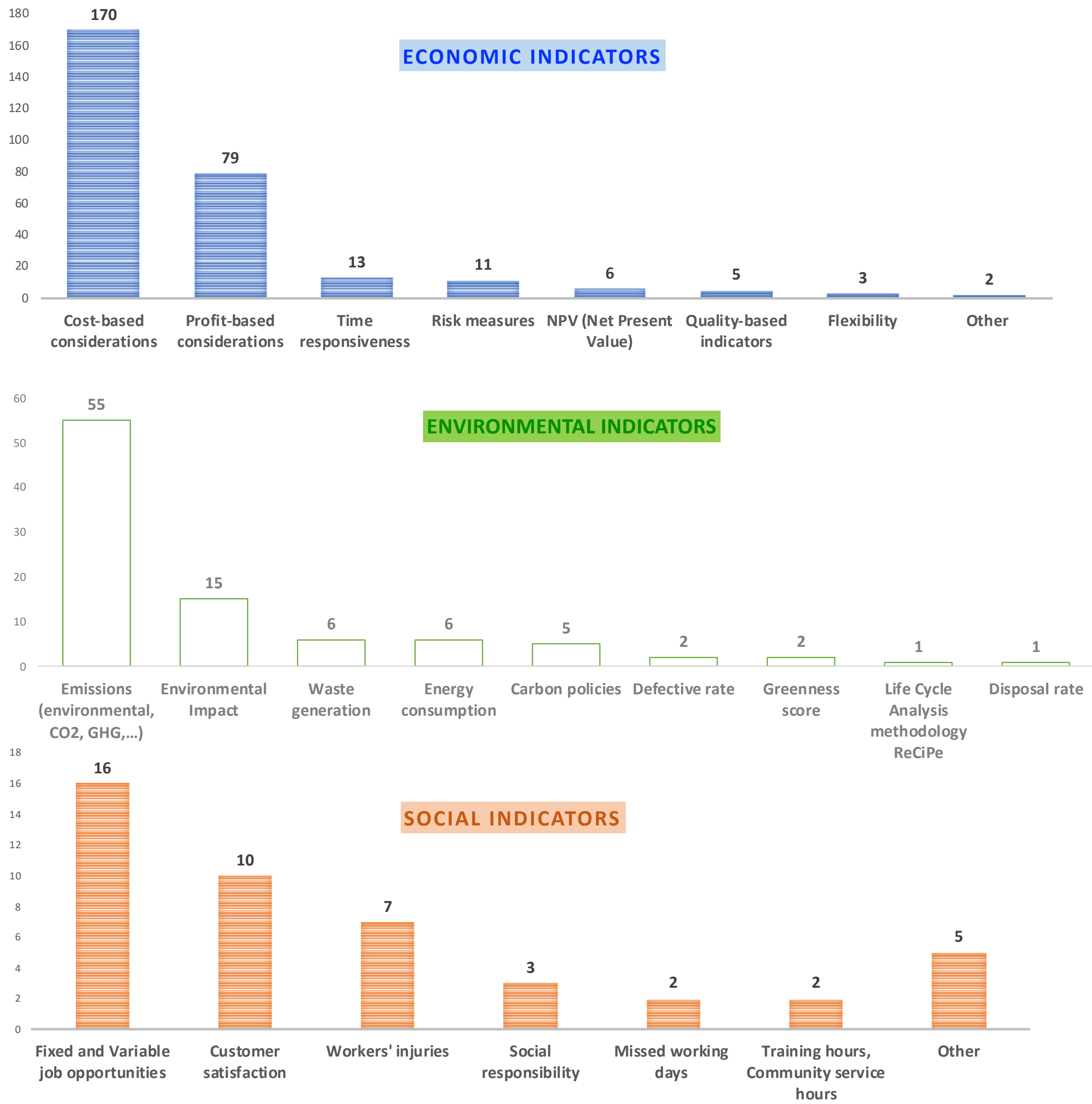

Figure 7. Economic, Environmental and Social Indicators

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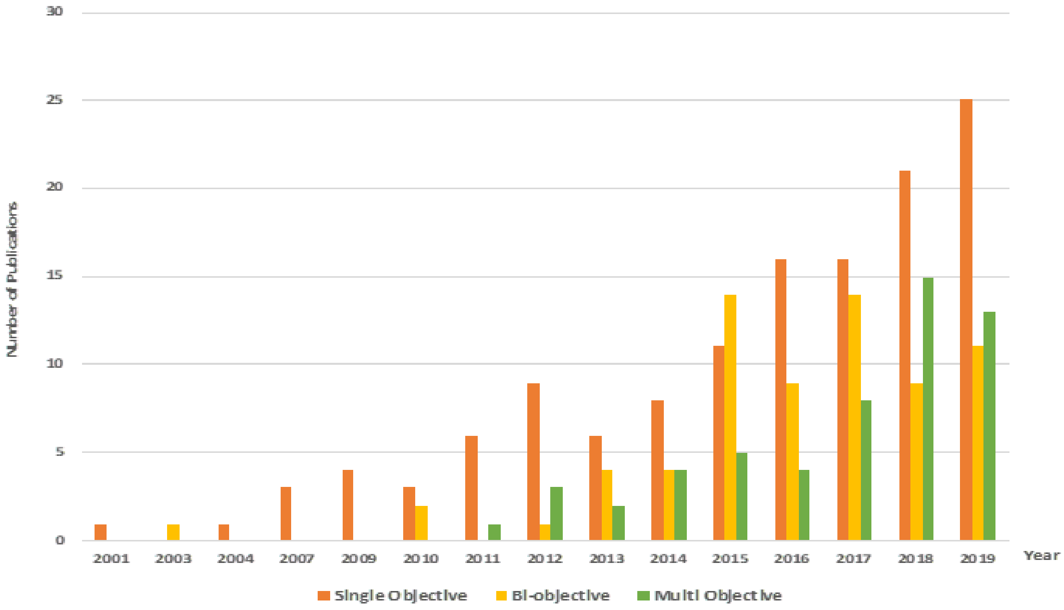

Figure 8. Yearly evolution of objective functions

5.7. Applications and Case Study Locations

Looking at the validation of the proposed models, it can be noticed that around 59% of all the reviewed articles are just validated through numerical examples, which use randomly generated data. The remaining papers are tested on case studies which are, to some extent, inspired by real-world situations. The geographical distribution of these case studies is presented in **Error! Reference source not found.**. The principal share (38%) of the models presenting a case study application are implemented in Iran. Outstandingly, the cases from this country were solely investigated in the period 2013-2019. European countries had a significant share with 24% of implemented case studies. This might be due the rising environmental awareness in European countries.

Table 6 classifies papers based on the industry sectors of related case studies. 21 categories are adopted, based on the nomenclature proposed by the Global Industry Classification Standard (GICS) (S&P Global & MSCI, 2018). Auto components displayed the highest frequency of case studies, representing 19% among all applications in real-world examples (Eren Özceylan et al., 2017; RajKumar and Satheesh Kumar, 2015; Üster et al., 2007). The second most referenced

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industry sector was Containers and Packaging, representing approximately 15% of the total cases (Baptista et al., 2019; Papen & Amin, 2019; Shamsi et al., 2019). Also, a significant number of applications can be retrieved in the following sectors: Electronic and Electric Equipment, Instruments and Components, Household Durables, Commercial Services and Supplies, as well as Food Products.

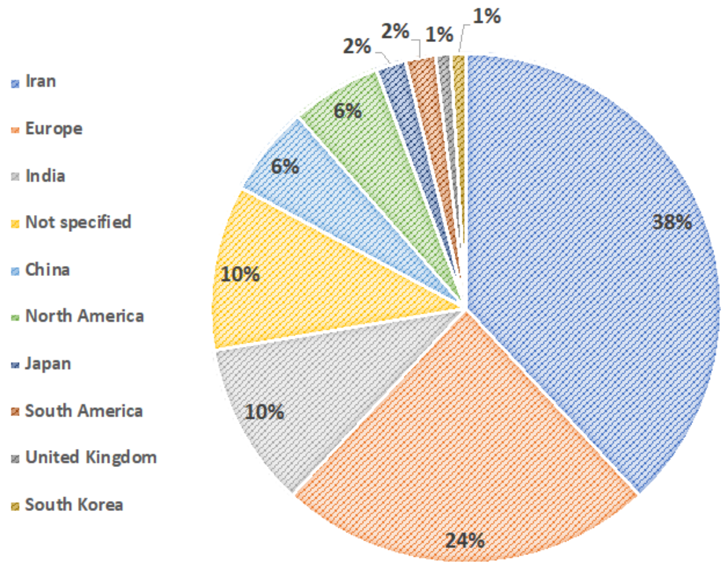

Figure 9. Case Study Locations

Table 6. Industry sectors

Industry	Number of publications
Automotive Components	21
Containers & Packaging	16
Electronic and Electric Equipment, Instruments & Components	13
Household Durables	8
Commercial Services & Supplies	7
Food Products	7
Generic Manufacturing / Not specified	7
Paper & Forest Products	6
Automotive	5
Metals & Mining	5
Health Care Equipment & Supplies	3
Fast moving consumer goods	2
Oil, Gas & Consumable Fuels	2

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Construction & Engineering	1
Energy Equipment & Services	1
IT Services	1
Generic Machinery	1
Media	1
Textiles, Apparel & Luxury Goods	1

5.8. Modelling approaches and solution techniques

Existing CLSC models can be classified into deterministic and non-deterministic ones (Figure 10). Non-deterministic models consider the uncertainty associated with some parameters such as demand or return quantity (Akçcal and Çetinkaya, 2011).

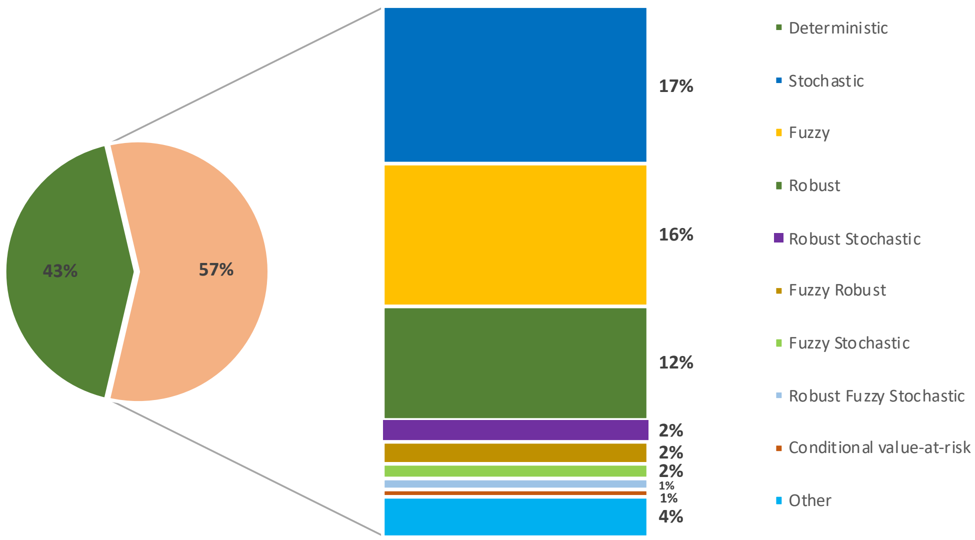

Figure 9. Deterministic and non-deterministic CLSC approaches

Table 7 illustrates different modelling approaches adopted in CLSCs; Mixed Integer Linear Programming (MILP) models are the most popular mathematical modelling approaches adopted by most scholars. In general, variations of Mixed Integer Programming (MIP) models are naturally suited to deal with these problems. Furthermore, approximately 57% of CLSC design problems are formulated through non-deterministic approaches due to the inherently uncertain nature of them. When it comes to non-deterministic models, apart from Mixed Integer Linear Programming, which is used thoroughly by authors, Stochastic programming, Fuzzy and Robust MILP are the most employed modelling approaches to deal with uncertainty in modelling design.

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It has to be remarked that, while a traditional SC is likely to face demand uncertainty, a CLSC goes beyond the delivery of products to the final customer. Thus, CLSC managers will be concerned not only with demand uncertainty but also with the fact that customers' returns are unknown; this can cause delays to take-back operations, and also to remanufacturing processes. (Akçcal & Çetinkaya, 2011) reinforced this observation by stating that the supply risk in a CLSC refers to the uncertainty in the quantity and quality of remanufactured products and recycled materials; additional risks can be identified in the cost of products to be reprocessed, in their quality, and in the environmental impacts associated with the recovery options.

Table 7. CLSC modelling approaches and solution methodologies

Modelling approaches	**NP**	**Solution Methodologies**	**NP**
Mixed Integer Linear Programming	111	Exact	115
Mixed Integer Non-Linear Programming	36	Metaheuristics	74
Mixed Integer Programming	25	Fuzzy optimisation	32
Stochastic Programming	10	Robust optimisation	13
Fuzzy Mixed Integer Linear Programming	8	Simulation	11
Linear programming	7	Heuristics	11
Fuzzy linear programming	4	Possibilistic approaches	9
Nonlinear programming	3	MCDM	7
Robust mixed integer linear programming	3	Stochastic optimisation	7
		Stochastic Robust optimisation	3

As such, modelling uncertainty is a fundamental component of CLSC models, with 146 out of the 254 reviewed papers attempting to do so. By scrutinising the body of the literature, it can be seen that the modelling of uncertainty has been implemented through a wide range of parameters, as illustrated in Table 8. Although uncertainty associated with customer demand, quantity of returns and relevant costs have been well investigated, the uncertainty associated with quality of returns is seldom considered in an explicit manner and deserves more attention. Also, the uncertainty associated with environmental impacts is considered just by a very few papers.

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Table 8. Uncertain Parameters

Uncertain Parameters and Variables	#
Customer Demand	103
Return Quantities	61
Costs	50
Capacity	26
Return Qualities	11
Price	11
Lead and Throughput Times	10
Risks	8
Disposal Rate	7
Supply	6
Collection rate	5
Manufacturing Rate	4
Carbon Emissions	4
Material flow	3
Distance between facilities	3
Transportation mode selection	2
Flexibility	2
Facility location	2
Supplier selection	2
Others	24

6. Discussion – a research agenda for CLSC research

While CLSCs can be seen as the backbone of the implementation of CE principles at a micro- and meso-level, most of the CLSC literature has been developed before the popularisation of the CE concept. As such, in this paper, a comprehensive review of modelling approaches for CLSC design problems has been conducted, with the primary objective of evaluating whether current modelling approaches are adequate for providing decision support for the transition towards a Circular Economy at a supply chain level. Previous literature reviews (See Table 1) revealed that a substantial amount of studies have been conducted in the field of CLSCs so far.

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The results of this review study illustrate an increasing academic interest CLSC design problems from 2012 onwards; the review also reveals that the subject has been widely studied in Asian countries due to pressing economic issues (related to the *closed* nature of certain national industrial systems) and environmental concerns. The analysis of the 254 considered articles has identified some crucial gaps, which should be considered by scholars in this field of study, synthesised as follows.

First of all, this field of study could benefit from a better empirical grounding. Most of the modelling approaches which have been analysed in this paper are not empirically validated through real-world case studies. In general, most of the proposed approaches are tested on numerical examples (often based on randomly-generated instances) which are devoid of real-life constraints. Just 38% of the considered papers provide some form of industrial applications; however, in many cases, the level of managerial implications provided is minimal, with no study performing longitudinal analysis on the long-term application of the models and little reporting about documented impacts on industrial operations. This seems to be a substantial gap in the current literature, which calls for modelling efforts with stronger empirical foundations and more significant attempts for real-world validation. This is a fundamental step to be undertaken in order to increase the industrial and practical relevance of CLSC research. This gap is further exacerbated by the geographical distribution of studies with a strong empirical component, which seem to be mainly from emerging economies, with a lack of real-world applications in European countries (Yang and Chen, 2019). Journals should devote specific attention to the promotion of empirically-grounded research, at the interface between academia and industrial practice, and encourage the development of research which is based on real-world application of CE practices in supply chains, along with a careful evaluation of results.

In terms of decision-making, most of the publications are concerned with strategic problems. Also, strategic issues in CLSCs (such as network design and facility location) are well integrated with tactical decisions (e.g. allocation); however, operational issues (like disassembly planning and scheduling) remain disjointed. In order to avoid sub-optimality, the development of novel approaches to incorporate all three decision levels appears to be a clear necessity in the literature. The design of specific decision support systems, based on multi-level modelling frameworks and capable of integrating different decision levels appears to be crucial.

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Figures also reveal that recycling is the most popular treatment policy among all recovery options in CLSC design papers, followed by remanufacturing. However, it can be noticed that approaches oriented to the minimisation of virgin resources consumption, which are one of the fundamental practices in a CE framework, were not covered in the analysed papers. It seems that most of the CLSC literature supports a "perennial growth" view which might be incompatible with an ambitious CE, mainly relying on a reductionist interpretation of CE based on eco-modernist and techno-optimistic paradigms (Genovese and Pansera, 2020; Bauwens et al., 2020). While it is becoming apparent that the transition towards a CE might follow very different patterns and lead to alternative futures (Bauwens et al., 2020), the dominant approach in the CLSC design literature is mainly aimed at *retrofitting* existing forward supply chains, rather than at the proposal of design configurations which are fully inspired by a CE paradigm, also by ultimately aiming to reduce production and consumption. These aspects have not been highlighted by previous literature reviews, which have mainly focused on the modelling aspects of CLSC design problems, rather than on their fundamental assumptions.

Such a reductionist view of CE is also apparent in the objectives which are considered in the analysed models. Although cost-related measures represent a vital performance measure for most companies, other goals should be taken into account as well, due to their importance and influence in the long run. However, as mentioned above, in terms of sustainability dimensions, most of the studies are mainly concerned with the modelling and optimisation of economic parameters. Environmental objectives predominantly appear to be rather a simple linear transformation of other indicators (e.g., transportation activities; CO_2-eq emissions), with no explicit consideration of CE-based indicators (e.g., depletion of virgin resources stocks; avoidance of virgin raw materials usage). As such, there is an obvious disconnection between circularity indicators and CLSC design models, which needs to be addressed in future researches, also trying to overcome the limitations of efficiency-based measures, which according to recent literature might not be enough to characterise the transition towards a CE (see, for instance, Bimpizas-Pinis et al., 2021).

Another apparent shortcoming of the considered literature, which has not been highlighted by previous literature reviews, is the fact that potential rebound effects associated with the implementation of CLSCs are completely overlooked. According to Zink and Geyer (2017), while attractive, the concept of closing material loops to preserve products, parts, and materials in the industrial system and extract their maximum utility, could be problematic. The idea of substituting lower-impact secondary production for environmentally intensive primary production gives CLSCs

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a strong intuitive environmental appeal. However, most of the papers tend to look at CLSC purely as a manufacturing and logistical system, overlooking the interaction of these production units with the economic dynamics, and thus providing a very simplistic representation of market channels in the body of literature. This is a significant shortcoming, as Zink and Geyer (2017) argue that CE practices, and the implementation of CLSCs, if not accompanied by a displacement of virgin resource consumption, can increase overall production, which can partially or fully offset their benefits. Circular economy rebound occurs when circular economy activities, which have lower per-unit-production impacts, also cause increased levels of production, reducing their benefit. The current CLSC design literature does not address potential CE rebound effects; for instance, design models do not assess the ability of secondary products to substitute for primary products, and price effects. Also, as mentioned above, the usage of very simplistic metrics and objective functions, which are mainly based on resource efficiency and productivity measures,

Also, the evaluation of the social dimension in CLSC design models seems to be generally overlooked, and conducted, at its best, with very simplistic measures (such as job creation and the stability of job opportunities). This is a crucial gap, as the social outcomes of the transition towards a CE are uncertain (Genovese and Pansera, 2020). While recycling and remanufacturing activities might create new jobs, the reduced reliance on raw materials extraction could undermine the performance of some more traditional industries, and have controversial impacts on local communities. The CLSC design literature seems to reflect, at a micro-level, some of the shortcomings of the general CE literature, in which the wider issues of the social pillar of sustainability and human development objectives (inequality and poverty, human rights and international justice) are largely neglected (Schröder et al., 2020). Advanced CLSC design models might have a great potential in evaluating the effect of CE practices at the supply chain level, which could also provide some micro-foundation for macroeconomic analyses. The holistic and whole-supply chain perspective of CLSC approaches could be beneficial for modelling, in an accurate way, the different labour intensity of different processes related to the implementation of CE practices across supply chains, taking a global perspective which could also help evaluating spill-over effects across different geographical regions. In general, CLSC design models could benefit from a better integration with Social Life-Cycle Analysis approaches, including an assessment of a wider set of dimensions, as detailed by Padilla-Rivera et al. (2020 and 2021). These include, but are not limited to: labour practices and decent work (e.g., labour management and industrial relations; occupational health and safety; fair workload allocation for workers; fair income distribution); human rights (e.g.,

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absence of child labour throughout the supply chain; absence of modern slavery practices; freedom of association and collective bargaining mechanisms for workers); wider societal issues (e.g., supplier assessments for impact on society; presence of anti-corruption mechanisms; social cohesion; respect of local communities; percentage of value added kept in local communities compared to linear supply chains); product responsibility (e.g., customer health and safety; product and service labelling; protection of customer privacy).

The relevance of economic, environmental and social criteria for the design of CLSCs clearly reveals the inherently multi-objective nature of such problems, which has also been highlighted by previous literature reviews (see, for instance, Govindan and Soleimani, 2017). However, the analysis of the literature has revealed that, while single objective models are successfully developed, the deployment of multi-objective optimisation approaches, still represents a gap in the literature. Therefore, the above-mentioned considerations call for further research dealing with multi-objective models incorporating criteria from all the three pillars of sustainability in order to accurately address complex CLSC design problems, and to provide realistic estimates about trade-off scenarios which could be related to the implementation of CLSC strategies. As argued by Gasparatos et al. (2009), the adoption of multi-criteria approaches for the evaluation of sustainability is an imperative, due to the multi-faceted nature of sustainability issues, and to the inherent limitations of the most commonly employed methods for assessing sustainability dimensions (inter alia, cost-based measures, LCA). The complex and adaptive nature of CLSCs needs to be described in a holistic manner through the synthesis of different non-reducible perspectives (Gasparatos and Scolobig, 2012). As such, further elaboration and refinement of current metrics, across all the sustainability dimensions, is needed in order to develop adequate frameworks for the evaluation of the performance of CLSCs; this aspect has not been previously highlighted by previously performed literature reviews. Such needs reflect the wider requirement for novel assessment methods and approaches which characterise the general CE debate, as also stated by Oliveira et al. (2021). Methodological developments are required in order to deal with large-scale multi-objective optimisation problems related to CLSC design issues. Also, traditional Operational Research and Management Science methods should be hybridised with detailed non-reductionist biophysical environmental assessment approaches, such as Life-Cycle Assessment and Emergy Accounting.

Furthermore, the proposed CLSC design models available in the literature fail to consider to a reasonable extent the need to organise adequate market channels for repaired, refurbished and

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remanufactured products. While some papers incorporate considerations about secondary markets, papers do not generally deal with the possibility of further extending product recovery options and market channels. This seems to suggest a need for more comprehensive CLSC design models, which could investigate the feasibility of more advanced CE strategies (involving a cascade of subsequent product reuses) in supply chains. Of course, the shift from linear to circular economy has a substantial impact on the design of supply chains and on their complexity. Undoubtedly, establishing multiple layers of facilities, serving multiple market channels, might lead to exceptionally complex modelling frameworks, which might require, in turn, innovative solution methods.

A further gap is represented by the limited integration between the current CLSC design literature and the most recent legislative initiatives in terms of CE. Recently promoted schemes (such as the Extended Producer Responsibility and Right-to-Repair ones, along with other initiatives aimed at reducing planned obsolescence) might have the potential to transform supply chains; as such, the CLSC design literature should pay attention to this rapidly changing landscape, investigating in a clearer way the impact of policy initiatives onto the shaping of supply chains. Modelling work aimed at analysing the readiness of existing supply chains to adapt to new legislation could be of great interest.

Table 9. Summary of research gaps and research agenda

Research Gap	**Related Agenda**
Lack of empirical grounding	Promotion of case-based research which can also foster knowledge transfer
Lack of multi-level decision-making integration	Multi-level decision-making models and frameworks
Focus on low R-imperatives	Better integration of high R-imperatives in mathematical models
Simplistic environmental performance assessment	Better integration of circularity measures in mathematical models; consideration of rebound effects and displacement issues
Lack of integration of social issues	Better integration of Social Life-Cycle approaches into modelling frameworks
Limited methodological developments	Development of multi-objective mathematical models and solution methods for dealing with the inherent complexities of CLSC design problems
Lack of integration with policy developments	Development of models and methods to assess the effects of policy developments, such as European directives

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6.1. Research Contribution

As such, this study makes several contributions to the existing knowledge by addressing the referred points:

• This research contributes with proactively planning for an optimal configuration to satisfy customer demands of different market levels. A strategic model is developed in a very generic and compact way based on mathematical programming formulation that can be adapted to any closed-loop supply chains readily. The compact representation of the MILP will significantly decrease the number of constraints that existing supply chain network design models tend to demonstrate.

• The model decides on the number of markets to serve across the whole supply chain. Hence, CLSC could have theoretically a numerable but infinite number of successive product downgrading. However, by activating a market level, the model can decide not to satisfy any demand at a certain market level, as there is no economic convenience.

• The proposed CLSC tends to maximise the number of products which once recollected from the customers, are in a way reutilise and send to farther customers, thus preventing manufacturing new objects from scratch. It will, therefore, determine at what point it's convenient to recycle products in such a way that we can measure the displacement ratio, therefore start buying fewer virgin materials from suppliers by using recycled materials. In this way, we can intensify the utilisation of EoL products with the aim of keeping the circle as small as possible, which is popular in circularity community. The more a product is used, the more value it can add to the economy.

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Part II

A Novel Mathematical Formulation for a Closed-Loop Supply Chain Design Problem

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie European Training Networks (H2020-MSCA-ITN-2018) scheme, grant agreement number 814247 (ReTraCE).

1. Problem Statement

Nowadays, it is crucial for companies to consider CE strategies while designing their CLSC networks. Therefore, a multi-objective, multi-product, multi-period, and multi-market channel CLSC decision-making problem is considered in this study according to CE principles, following up on the gaps identified in Part I of this report. In a multi-period environment, a company manufactures, distributes and sells the products to its primary customers and decides how to establish a CLSC in compatible with CE framework, whether and how to activate other market levels, which treatment approaches should be adopted in the backward flow and how to integrate them into the existing forward infrastructure. In other words, the main focus of this research is on extending products' life cycle by keeping them in a circle for as long as possible so that we can reduce the waste by minimizing the disposed amount of End-of-Life (EoL) products.

The main focus of Circular Economy is on materials circulating throughout the whole supply chain. As such this research tries to use Secondary materials in compatible with Circularity principles. Figure 11 represents the proposed network of the CLSC configuration with 9 echelons. As the diagram demonstrates, the nodes of the forward supply chain, which includes suppliers, plants, distributors and primary customers, are linked through solid lines; the dashed lines show the potential nodes of the reverse logistics such as collection and inspection centres, disposal centres, recyclers, remanufacturers and reusing centres. As illustrated in the figure, there are various market levels based on the number of times the products are returned to collection/inspection centres at the end their life. Market levels are referring to appropriate channels where returned products (reused, remanufactured and recycled) can be resold to customers after one or several utilisations; companies can therefore generate further revenues from such products. As such, multi-level markets are denoting to where business organisations are able to resell their returned products at a discounted price, after downgrading them by performing the relevant recovering processes and therefore making more profit. In practice, secondary and multiple levels of markets are key channels to sell EoL products and CLSCs are an effective means to perform the corresponding operations. This is a common practice in Electric and Electronics sector, where an EoL product is introduced to the market after several utilisation according to its life cycle instead of being disposed (Guo et al., 2018). Several studies have investigated the impact of incorporating the secondary markets on the supply chain performance (He & Zhang, 2010; Lee & Whang, 2002). In this regard, according to (Lee & Whang, 2002) secondary market creates two interdependent effects on supply

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chain, namely a quantity effect which is related to the sales by a manufacturer and an allocation effect regarding the supply chain performance. In general, the positive impact of the secondary markets on the supply chain performance has been proven (He & Zhang, 2010). However, this study is the first attempt to consider the dynamic interaction between multiple levels of markets in a CE-based CLSC set, and hence it can well represent the real-world issue.

In forward logistics, the suppliers deliver virgin raw materials to producers. Actually, there are two types of materials which are the main inputs for plants throughout the network. First kind of materials are virgin raw materials that are produced from their original natural resources which are mainly used in the primary market. Second type of materials are non-virgin raw materials which are recycled parts of EoL products from previous market levels and can be used in downgraded products.

In the reverse logistics, the returned goods are gathered from primary customers by collection and inspection centres to be examined and sorted based on their quality level that can be further processed and treated. In the proposed model, three treatment strategies are considered for the returned products in the backward flow:

(i) ***Reusing:*** the returned goods are of good quality that can be reused and directly sent to distribution centres. They are sold at a discounted price as downgraded products after cleaning/repairing;

(ii) ***Remanufacturing:*** the returned products are reprocessed and converted into "like new" condition for resale. Remanufacturing involves disassembling EoL goods, substituting any broken components, repairing any remaining flaws, and repacking the returned product for sale as a remanufactured item (Abbey et al., 2015).

(iii) ***Recycling:*** the returned products that are not suitable for remanufacturing, are recycled at recycling centres and the materials are reused as a displacement of virgin raw materials by suppliers; on the other hand, it generally refers to the applicable operations that involve the reprocessing of waste for the purpose of extracting valuable raw materials.

In doing so, the recovering centres target the EoL products to be re-introduced into the economy considering their economic value and environmental benefits. This process will continue till the product reaches its end of life and none of the components and materials are not usable any more. Finally, the fraction of returned products which have low quality are sent to the disposal centres

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for final treatment. Therefore, we have considered further round for markets in order to keep EoL products as well as their components and parts for as long as possible in the supply circle. Hence, the returned products from secondary markets that are usable one more time, are sent to collection and inspection centres to be examined for further treatment processes and the loop is reiterated.

Strategic planning implicates the highest management level for major investments targeted at long-term goals and deterministic approaches are viewed as a suitable approximation of reality that is easier to build and interpret than a stochastic model. Therefore, duo to the strategic nature of the model, it is reasonable to assume deterministic parameters. There is no loss of generality, as these can be the average arising from a probabilistic distribution.

Designing such a circular network and determining the specific locations to establish different facilities and identifying the number of optimal market levels for a specific product at a certain time period, requires taking various objectives into account subject to different constraints. As such, the objectives of this model are to maximise the total profit, which is the key motivation for companies to pay attention to CLSCs and embedding CE practices in their operations; and to minimise the total number of discarded products, which has been overlooked in the existing literature while it can improve the overall performance of CLSC in terms of sustainability and CE metrics. The existing environmental related objective functions, normally are not addressing the circularity in CLSCs. In this study, the model creates incentives to keep products in circulation for as long as possible. These objectives can be obtained through making the optimal decisions on node location, number of market levels, transportation quantities and considering distinctive recovery options simultaneously, such as reusing, remanufacturing and recycling.

As such, to locate the facilities and activate market levels reflecting the concept of downgrading products in different strategic time periods, it is assumed that the number of the EoL products returned to the collection and inspection centres is a fraction of the customer demands at market level from the previous time period ($d_{1t} \geq d_{2t} \geq \ldots \geq d_{lt}$). This assumption is critical for modelling this problem, which implies that demands for downgraded products are assumed to be decreasing throughout the time horizon. The number of repetitions of the market levels, can be determined depending on the product features and customer demand. Moreover, given the environmental constraints, the company can decide about the optimal level of demand to meet.

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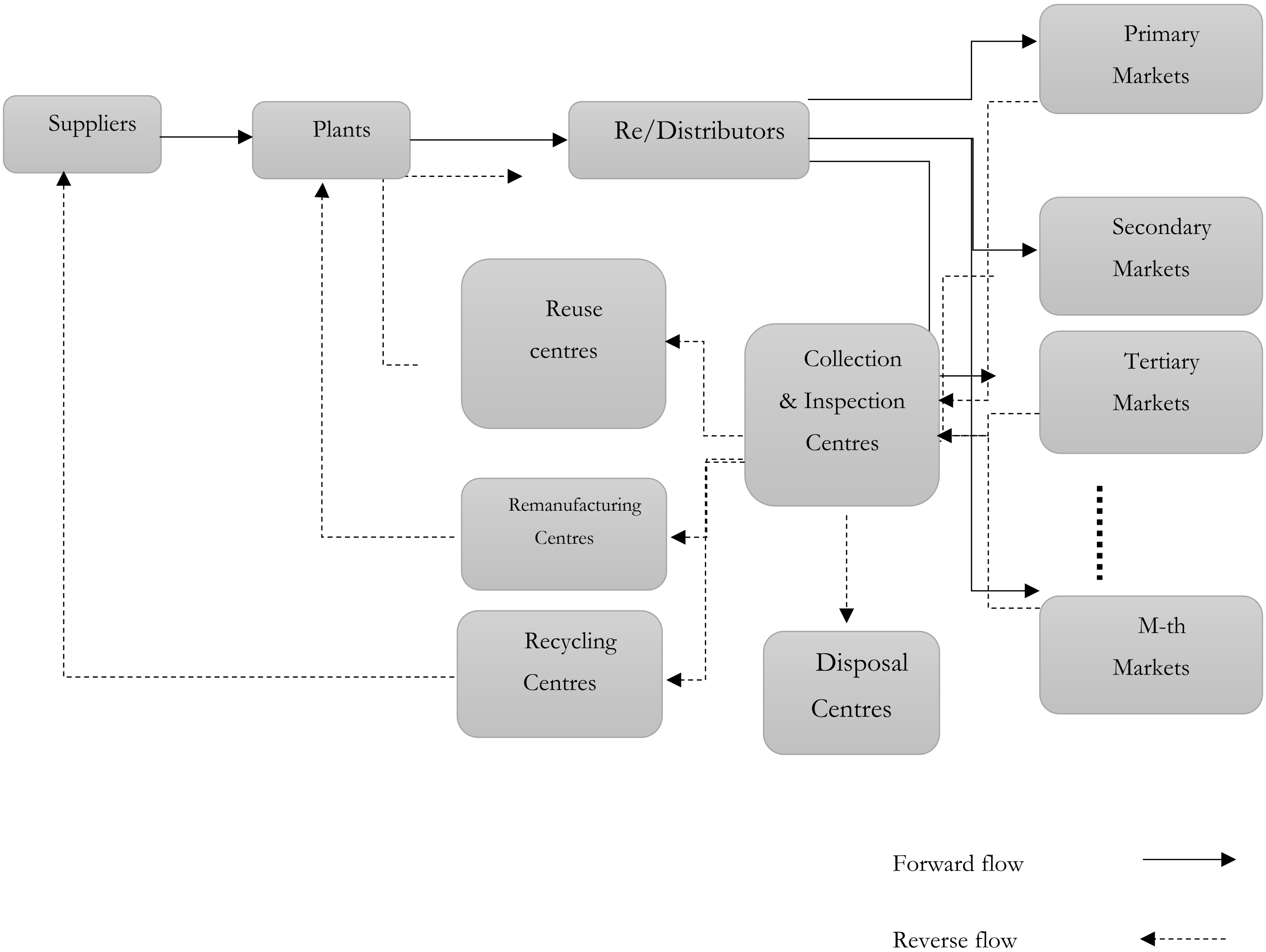

Figure 10. CLSC structure and Schematic illustration of product flows in forward and reverse flows

1.1. Mathematical Formulation of CLSC

This section shows that how the proposed approach outperforms other existing CLSC optimisation models. The very compact and comprehensive manner of the presented reliable formulation can be mentioned as one of the great merits of the proposed design that can be readily adapted to various types of CLSCs. It declares a sort of redundancy that arises from the growth in the number of equations in the existing CLSC networks. Figure 12 demonstrates the key components of the mathematical formulation (e.g. inputs, objective functions, constraints and outputs) in a conceptual framework. Accordingly, the main outputs of this model are as follows:

• To determine the facilities' location(s).

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• To determine the product flow among network facilities to maximise the profit and minimise the amount of disposed products.

• To determine the number of market levels to be activated through the network. In practice, CLSCs provide an effective means to collect returned goods and perform the relevant treatment strategy, while (multi-level) markets are the significant channels to sell all those (primary/recovered) products.

• To determine the amount of raw and recycled materials supply level. The model tries to use recycled materials as a substituent for virgin raw materials for as much as possible.

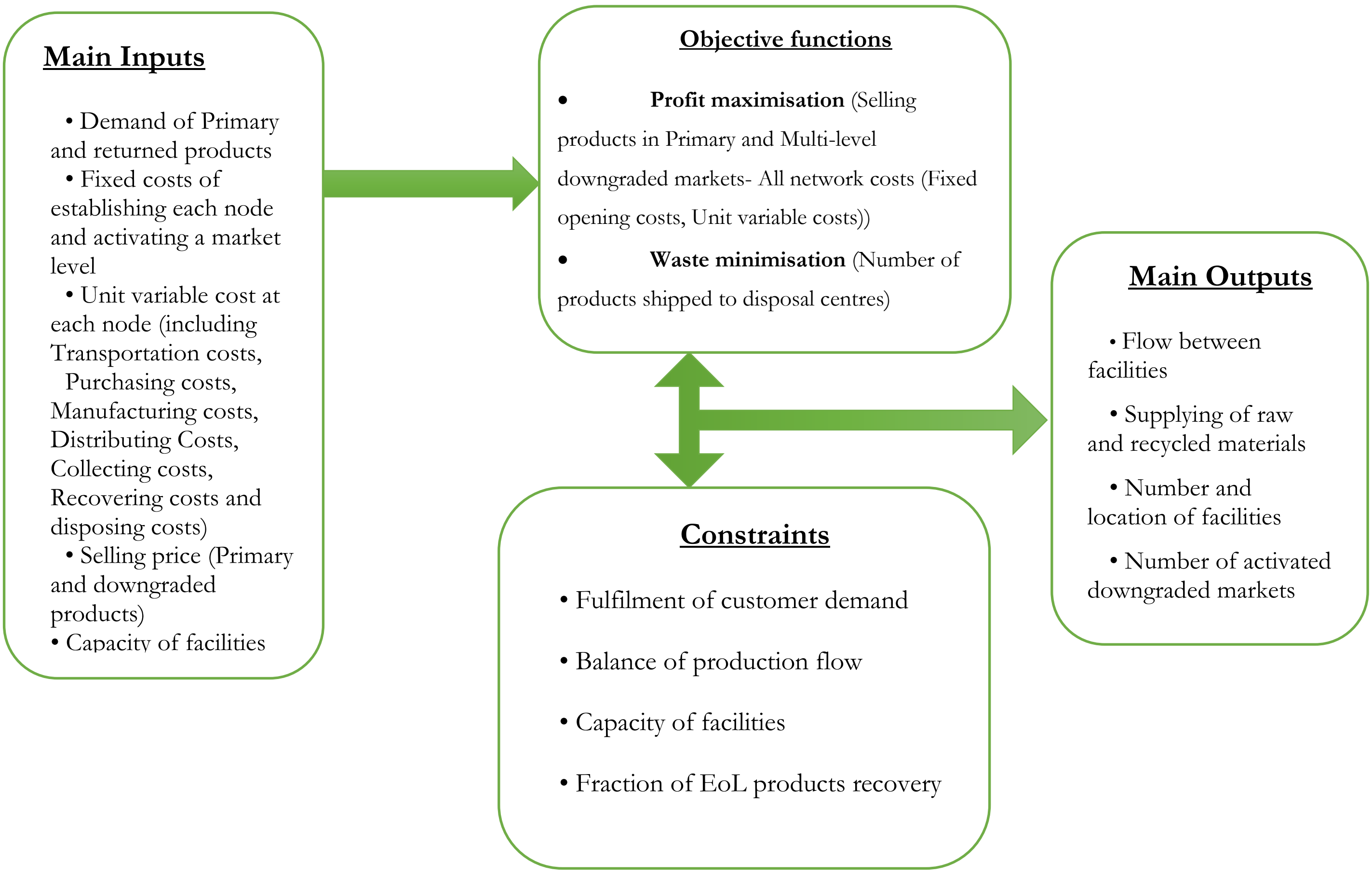

Figure 11. Conceptual framework of CLSC mathematical model

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Table 10 presents the notations used in the mathematical formulation of the proposed CLSC network.

Table 10. Model notation

Indices:	
(i,j)	Set of indices denoting the nodes
a	Index of arcs between node i and j in $(i,j) \in A$
l	Market level in $L = \{1,2,\dots,l\}$
k	Product types in $P = \{1,2,\dots,k\}$
t	Time periods in $T = \{1,2,\dots,t\}$
Sets:	
N_s	Set of supplier nodes
N_m	Set of potential locations for establishment of manufacturing centre nodes
N_d	Set of potential locations for establishment of distributor nodes
N_c	Set of customer zones
N_e	Set of potential locations for establishment of collection and inspection centre
N_u	Set of potential locations for establishment of reusing nodes
N_r	Set of potential locations for establishment of remanufacturer nodes
N_y	Set of potential locations for establishment of recycler nodes
N_p	Set of potential locations for establishment of disposal centre nodes
N	Set of all nodes$\{N_s \cup N_m \cup N_d \cup N_c \cup N_e \cup N_u \cup N_r \cup N_y \cup N_p\}$
TN	Set of treatment nodes $\{N_u \cup N_r \cup N_y \cup N_p\}$
BN	Set of backward nodes$\{N_c \cup N_e \cup N_u \cup N_r \cup N_y \cup N_p\}$
Parameters:	
m	Fixed cost of activating a market level (e.g. administrative and marketing expenses)
f_i	Fixed cost of activating nodes
C_i	Capacity associated to node
c_a	Unit variable cost of arc a; note this includes both processing cost at node i and
d_t^{lk}	Demand level for product k in l-th market level at time period
p_k	Selling price level per unit of product k to customer centres
φ_{lk}	Discount percentage of price of the primary product k at market level l
δ_i	Recovery rate at recovery centre RN
α_i	Delay associated with node i
β_i	Downgrade level at node i
γ_t^{lk}	Cannibalisation ratio (demand leakage) of product k at time period t in l-th market
Integer decision variables:	
x_{at}^{lk}	Flow of products in arc a at time period t for product k in l-th market level
s_{it}^{lk}	Supply level in node i at time period t for product k in l-th market level
Binary decision variables:	
y_{it}^{lk}	1 if node i is to be activated; 0 otherwise
z_t^{lk}	1 if l-th market level at time period t for product k is to be activated; 0 otherwise

The proposed model can be formulated as a mixed-integer linear programming problem. The first objective function (1) maximises the total profit by subtracting the total revenues of the whole

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CLSC network (first component) from the overall costs. Revenue streams include the profit gained by activating primary, secondary or l-th level of market from selling different types of products with different price levels at period t. Technically, the price of all downgraded products will be a percentage of the original primary products price (k). In other words, the recovered units will be sold at a discounted rate (φ) to the customers. Besides, the total supply chain costs calculate the operation cost of activation of a specific market level, fixed costs of establishing each facility, and unit production cost for a certain product at period t.

$$max\ obj_1 = \sum_{\substack{a:(i,j)\in A\\ j\in N_c}} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} \varphi_{lk}.P_k.x_{at}^{lk} - \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} m.z_t^{lk}$$

$$- \sum_{\substack{i\in N\\ i\neq N_c}} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} f_i.y_{it}^{lk} - \sum_{a\in A} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} c_a.x_{at}^{lk} \quad (1)$$

To adjust the second objective function, the overall time from production to disposal is considered; in this way, the generated waste flow is discounted based on the market levels they are collected from. Since this function is to be minimised, dividing the amount of disposal by the respective market level will make sure the use of disposal is more convenient at lower market levels, namely, after multiple utilisations of the product; this will provide an incentive to the firm to activate further market levels. Essentially, disposing a product after one use counts as a full disposal; after *n* uses in successive markets would be discounted by a factor $1/_n$. Hence, the second objective function (2) aims to minimize the total amount of products transported to disposal centres in order to make CLSC network as circular as possible, which can be defined as follows:

$$min\ obj_2 = \sum_{\substack{a:(i,j)\in A\\ j\in N_p}} \sum_{l\in L} \sum_{k\in P} \sum_{t\in (1,T-1)} x_{at}^{lk}/l \quad (2)$$

In terms of constraints, Capacity constraint (3) indicates that, in each period, the total amount of shipped products from node *i* to node *j* should be lower than the capacity of node *i*.

s.t:

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$$\sum_{a:(i,j)\in A} x_{at}^{lk} \leq C_i . y_{it}^{lk} \qquad \forall\, i \in N, t \in T, k \in P, l \in L \qquad (3)$$

Balance constraint (4) is one of the well-known constraints in CLSCs that ensures in each period, the output of a node should be equal to its input.

$$\sum_{\substack{a:(i,j)\in A, j\neq N_p \\ l+\beta_i \leq L \\ t+\alpha_i \leq T}} x_{a(t+\alpha_i)}^{(l+\beta_i)k} + \sum_{\substack{a:(i,j)\in A, j=N_p \\ t+\alpha_i \leq T}} x_{a(t+\alpha_i)}^{lk}$$

$$- \sum_{a:(i,j)\in A, j\neq N_e} x_{at}^{lk} - \sum_{\substack{a:(i,j)\in A, j=N_e \\ t+\alpha_i \leq T}} x_{a(t+\alpha_i)}^{lk} = S_{it}^{lk} \qquad \forall\, i \in N, t \in T, k \in P, l \in L \qquad (4)$$

Constraint (5) expresses that the number of products shipped to customer zones should be less than or equal to customer demands for product *k* at time period t. $(\gamma_t^{qk} . z_t^{qk})$ actually shows how the recovered products of the downgraded markets could cannibalise the new products sale.

$$\sum_{\substack{a:(i,j)\in A \\ j\in N_c}} x_{at}^{lk} \leq d_t^{lk}\left(1 - \sum_{q\in(l+1,|L|)} \gamma_t^{qk} . z_t^{qk}\right) \qquad \forall\, t \in T, k \in P, l \in L \qquad (5)$$

Constraint (6) ensures that at least a certain percentage of the returned products from market level l is being recovered (reused, remanufactured or recycled).

$$x_{a(t+\alpha_i)}^{(l+\beta_i)k} \geq \delta_j . \sum_{\substack{a:(j,i)\in A, \\ j\in N_e}} x_{a(t+\alpha_i)}^{lk} \qquad \forall\, a: (i,j) \in N_c, j \in RN;\ \forall\, t \in T, k \in P, l \in L \qquad (6)$$

Constraints (7) ensures that at the first time period, there should be no transportation flow among backward facilities, similarly constraints (8) restricts the reverse flow at the first market level.

$$\sum_{a:(i,j)\in A} x_{at}^{lk} = 0 \qquad \forall\, i \in BN \neq N_p, \forall\, t \in T: t = 1, k \in P, l \in L \qquad (7)$$

$$\sum_{a:(i,j)\in A} x_{at}^{lk} = 0 \qquad \forall\, i \in RN, \forall\, t \in T, k \in P, l \in L: l = 1 \qquad (8)$$

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Constraint (9) forces the activation of markets levels being consistent with nodes.

$$y_{it}^{lk} \leq z_t^{lk} \qquad \forall\, i \in N, \forall\, t \in T, k \in P, l \in L \tag{9}$$

Constraint (10), denotes that if a node established at a certain time period, it should always remain open. This is due to the fact that opening network facilities with certain capacities have a costly and lasting impact in the fixed network costs. Therefore, the opened facilities in each strategic time period cannot be closed during the next time periods, and should remain operational till the end of the time horizon under investigation.

$$y_{i(t-1)}^{lk} \leq y_{it}^{lk} \qquad \forall\, i \in N, \forall\, t \in T: t \neq 1, k \in P, l \in L \tag{10}$$

Similarly, Constraint (11), demonstrates that if a level of market established at a certain time period, it should remain open for the next time periods as well, till the end of the time horizon under investigation.

$$z_{(t-1)}^{lk} \leq z_t^{lk} \qquad \forall\, t \in T: t \neq 1, k \in P, l \in L \tag{11}$$

Of course, constraints (10) and (11) could also be relaxed in order to provide more flexibility to the firm; however, appropriate penalties should be defined in order to take into account the cost of closing a given market level.

Constraint (12) represents the non-negativity and integrality of variables and the ranges each variable can adopt according to their specific features.

$$x_{at}^{lk} \geq 0, s_{it}^{lk} \in \mathbb{R} \begin{cases} \geq 0, & i \in N_s \\ \leq 0, & i \in N_p \\ = 0, & otherwise \end{cases}, \quad y_{it}^{lk} \in \{0,1\}, z_t^{lk} \in \{0,1\} \tag{12}$$

As it can be seen, a very compact and comprehensive mathematical CLSC formulation is introduced, also thanks to the capability of the model to represent all the facilities and flows in the model through an aggregate description. Table 11 provides a comparison of the number of parameters, decision variables and sets of equations required to operationalise objective functions and constraints, to the ones employed in comparable studies in the literature. It can be seen that the model proposed in this study allows maximising the compactness of the formulation.

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Table 11. Number of Parameters, decision variables (DVs) and Equations in comparable CLSC formulations

Paper	No. of parameters	No. of DVs	No. of equations (Objective functions & Constraints)
(Ren et al., 2020)	44	12	31
(Darestani et al, 2019)	47	25	39
(Atabaki et al., 2019)	62	28	50
(Pourjavad & Mayorga, 2019a)	42	26	47
(Sahebjamnia et al., 2018)	69	11	22
This study	**11**	**4**	**12**

2. Solution methodology

One of the most challenging phenomenon in multi-objective problems is the coexistence of conflicting goals which need to be optimised at the same time. The proposed model reveal includes two conflicting objective functions (maximisation of the economic objective and minimisation of the environmental impact); hence a trade-off between these objectives can be observed. In order to cope with the presence of multiple conflicting objectives, the identification of the set of Pareto-optimal solutions constitutes one of the most popular approaches (Mavrotas, 2009) . This technique enables decision-makers to identify a set of non-dominated solutions, among which the preferable alternatives can be identified.

The improved version of the ϵ-constraint method developed by Mavrotas & Florios (2013), named AUGMECON2, represents one of the most prominent techniques to deal with multi-objective problems; such approach is able to find efficient solutions for both convex and non-convex functions (Ahmadi & Amin, 2019). Given its good performance, documented in the literature, AUGMECON2 is therefore applied to solve this CLSC problem as it has been proved that has better performance than other methods.

This approach tends to convert a multi-objective model to a single-objective one in a way that, through successive steps, one objective function is assumed to be the main objective and the remaining ones are considered as constraints as shown below:

$$max f_1(x) + eps \times \frac{s_2}{f_{max_2} - f_{min_2}} \tag{13}$$

s.t:

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$$f_2(x) - s_2 = f_{max_2} + t \times \frac{f_{max_2} - f_{min_2}}{q_2}$$

$$x \in S \; and \; s_i \in R^+$$

In equation (13), f_1 and f_2 correspond, respectively, to the economic and environmental objectives; s_2 represents the slack variable for the second objective (f_2). The f_{max_2} and f_{min_2} represent the maximum and minimum values of the objective function. In order execute a lexicographic optimization, the first objective is considered with a negative sign. As a result, the solver will find an optimal value for f_1 and then will optimise the second objective function (f_2) (Mavrotas & Florios, 2013). Moreover, ε is a fairly small number between 10^{-6} and 10^{-3} (Mavrotas & Florios, 2013).

The method considers one objective function at the time, keeping the remaining ones as constraints; this process is then repeated for all the objective functions. The flowchart of the AUGMECON2 algorithm is illustrated in Figure 13 (adopted from (Mavrotas & Florios, 2013)). The main advantage of AUGMECON2, as compared to other methods, is the presence of bypass jumps. The bypass coefficient shows how many consecutive iterations the method can skip in order to avoid redundant iterations (Mavrotas & Florios, 2013). As such, according to AUGMECON2, the RHS of each objective function can be obtained by dividing the range of each objective function to equal intervals using intermediate grid points (Mavrotas & Florios, 2013). The larger the number of grid points, the better the representation of the Pareto-optimal set, with a higher required computational time though.

Finally, the MILP model and the implementation of the AUGMECON2 method have been coded in a Python programming language environment, and using the CPLEX solver, which is one of the most powerful optimisation software packages for solving mixed-integer programming models, with the objective to plot a set of Pareto-optimal solutions for a set of test-instances.

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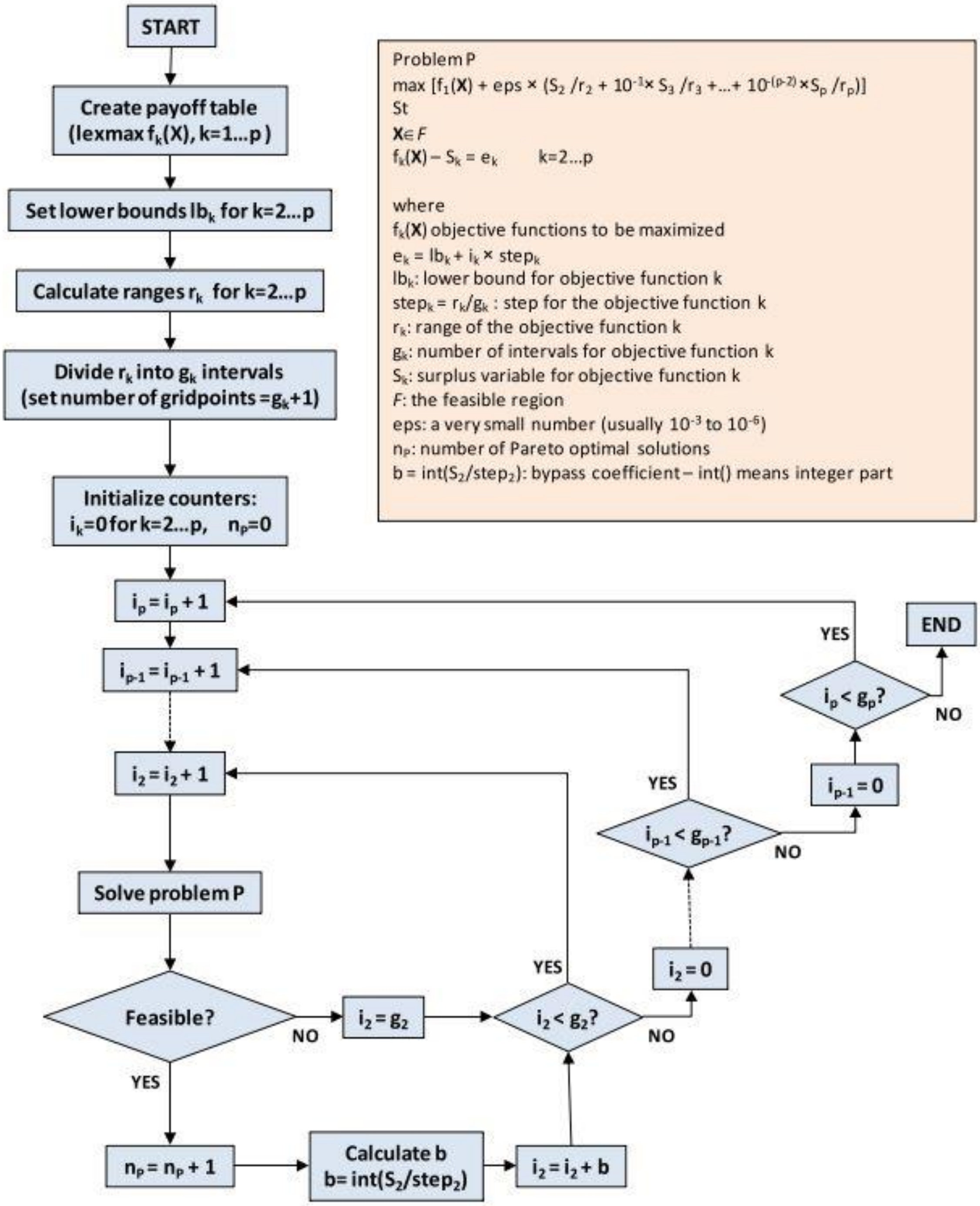

Figure 12. Flowchart of AUGMECON2 method (from Mavrotas & Florios, 2013)

Given that the proposed mathematical model has two objective functions, the solution would be a set of Pareto-optimal frontier solutions. In order to obtain the non-dominated Pareto-front solutions, the objective functions should be minimised simultaneously. Hence, the lexicographic

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AUGMECON2 approach is used and the first objective function (Profit maximisation) is considered as the main objective. As a result, the final set of solutions at the end of exploration stage will include the so-called non-dominated solutions, which will represent the set of efficient alternatives across the considered objective functions (Devika et al., 2014).

3. Experimental evaluation

The supply chain optimisation models established in the literature are mostly problem-specific (Zeballos et al., 2018) or based on some randomly generated parameters. In this section, numerical experiments are conducted to validate the performance of the proposed mathematical model and verify the solution methodology. Numerical analyses are also carried out to provide managerial insights into the circular-based closed-loop networks. The details of generated data are described in the following subsections.

3.1. Data generation

Appropriate setting of the parameters lead to more reliable and robust solutions (Devika et al., 2014). In this regard, the testbed of this specific problem is based on benchmark instances employed by similar CLSC models in the literature (Devika et al., 2014; Hamed Soleimani & Kannan, 2015) as represented in the following tables.

It must be noted that the number of facilities to be considered in the problem has a substantial impact on the size of the supply network (Yavari & Geraeli, 2019). In this regard, to determine the cardinality of the sets and the values of other parameters, a careful scrutiny and review of the literature has been conducted (Table 12 and Table 15). The cardinality of typical facilities sets in comparable problems has been reviewed; then, ratios among the cardinalities of sets of facilities have been derived, and appropriate ranges for parameter values are calculated as shown in Table 13 and Table **16**. As a result, more realistic cardinalities for considered sets (**s**: suppliers, **m**: manufacturers, **d**: distributors, **c**: customers, **e**: collection/inspection centres, **u**: reusing centres, **r**: remanufacturers, **y**: recyclers, **p**: disposal centres) and appropriate values for parameters have been employed in the computational experiments.

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Table 12. Number of facilities

Paper	s	m	d	c	e	u	r	y	p	Data Type
(Saedinia et al., 2019)	3	4	7	28	3	-	-	3	2	Test instance
(Ren et al., 2020)	-	3	5	-	7	-	-	5	2	Real-world problem
(Devika et al., 2014)	-	4	7	-	3	2	-	2	-	Real-world problem
(Devika et al., 2014)	8	4	8	12	8	2	3	2	2	Test instance
(Mohammad Bagher	8	4	2	8	12	-	-	-	-	Test instance
(Shen, 2019)	-	6	-	15	10	-	-	4	-	Test instance
(Tosarkani & Amin,	5	6	-	15	-	-	2	-	-	Real-world problem
(Ahmadi & Amin, 2019)	5	4	15	44	7	-	5	-	3	Real-world problem
(Masoudipour et al.,	-	2	2	7	2	-	1	-	-	Test instance
(Shamsi et al., 2019)	2	1	3	-	-	-	-	-	-	Real-world problem
(H. Guo et al., 2019)	-	5	-	30	-	-	-	-	-	Test instance
(C. Yang & Chen, 2019)	2	4	6	20	2	-	-	-	-	Test instance
(Baptista et al., 2019)	-	3	3	18	3	-	-	-	-	Test instance
(Papen & Amin, 2019)	5	3	6	-	6	-	-	-	-	Real-world problem
(S.A. Darestani &	3	3	3	4	2	-	2	2	-	Test instance
(Polo et al., 2019)	-	5	4	7	-	-	-	-	4	Real-world problem
(Sherif et al., 2019)	2	1	14	35	14	-	-	3	1	Real-world problem
(Almaraj & Trafalis,	3	2	3	5	3	-	-	-	2	Test instance
(Almaraj & Trafalis,	5	3	5	10	5	-	-	-	3	Test instance
(Almaraj & Trafalis,	7	5	7	20	7	-	-	-	5	Test instance
(Zhen, Huang, et al.,	-	5	7	7	-	-	-	-	-	Test instance
(Yadegari et al., 2019)	-	5	3	4	2	-	1	-	-	Test instance
(Fazli-Khalaf et al., 2019)	-	6	5	9	-	-	-	4	-	Real-world problem
(Taheri-Moghadam et al.,	-	2	2	2	-	-	-	-	-	Test instance

To evaluate the performance of the proposed model as well as the solution methodology, four classes of problems with different sizes are defined, as represented in Table 13. In the following, for sake of simplicity, some early computational results for the class of the small-sized problems (P1) are reported.

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Table 13. Problem sizes

Problem levels	Problem	s	m	d	c	e	u	r	y	p	Total
Small scale	P1	2	1	3	6	3	1	1	2	1	20
Medium scale	P2	4	2	6	12	6	2	2	4	2	40
	P3	6	3	9	18	9	3	3	6	3	60
Large scale	P4	8	4	12	24	12	4	4	8	4	80

Due to the strategic nature of the model, pre-determined bounds for each of the R-options are derived by calculating the average values in the literature as shown in Table 14.

Table 14. Parameters ruling acceptable ranges for recovery options

Paper	Reusing rate		Remanufacturing rate		Recycling rate	
	Min	Max	Min	Max	Min	Max
(M. Ramezani et al., 2013)	0.45	0.45	0.25	0.25	0.15	0.15
(Devika et al., 2014)	0	0.5	0	0.5	0	0.5
(Magdalini A. Kalaitzidou et	0.4	0.4	0.3	0.3	0.2	0.2
(Atabaki et al., 2019)	0.2	0.2	0.3	0.3	0.3	0.3
Average	0.35	0.39	0.28	0.34	0.22	0.29

Table 15. Selling price of brand new products

Paper	Min price	Max price
(Faccio et al., 2011)	200	500
(M. Ramezani et al., 2013)	120	140
(Keyvanshokooh et al., 2016)	160	230
(Jeihoonian et al., 2016)	600	1300
(Ahmadi & Amin, 2019)	100	100
(Atabaki et al., 2019)	50	95
Average price value	**200**	**400**

The values of some parameters are presented in Table 16. For each parameter, appropriate ranges, based on similar studies available in the literature, have been established. For the generation of the computational testbed, instances have been generated in a randomised way, considering uniform distributions for all the parameters, within the specified ranges. For instance, in terms of customer demand, yearly values have been considered, within an appropriate range. It is worth to note that, given the presence of markets for reused and remanufactured products, a fraction of the

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demand for primary products might be cannibalised by the existence of the downgraded products. Therefore, the value of the demand is multiplied by a uniform fraction $\gamma_t^{lk} \sim \mathrm{U}\,(0{,}0.5)$ which represents this cannibalisation effect. Also, c_a is considered as the average total cost of all variable costs related to each facility including purchasing, manufacturing, distributing, collecting, recovering, disposing and transporting a product which is produced or taken back to the relevant stage in both forward and reverse supply chains.

Table 16. Parameters and their values

Parameters	Definition	Values
L	Number of market levels	5
P	Number of market levels	2
T	Number of Periods	12
d_t^{lk}	Total demand for all customer nodes	10000
f_i	Fixed cost of starting a contract with supplier s	~ U (1100,3300)
	Fixed cost of opening a plant m	~ U (110000,330000)
	Fixed cost of establishing a distribution centre d	~ U (20000,70000)
	Fixed cost of establishing a collection centre e	~ U (25000,75000)
	Fixed cost of establishing a reusing centre u	~ U (3000,10000)
	Fixed cost of establishing a remanufacturing centre r	~ U (50000,150000)
	Fixed cost of establishing a recycling centre y	~ U (20000,55000)
	Fixed cost of establishing a disposal centre p	~ U (65000,200000)
M	Fixed cost of activating a market level	~ U (10000,50000)
C	Capacity level of supplier s	~ U (1100,3300)
	Capacity level of plant m	~ U (5000,15000)
	Capacity level of distribution centre d	~ U (3000,9000)
	Capacity level of collection centre e	~ U (2500,7500)
	Capacity level of reusing centre u	~ U (300,1000)
	Capacity level of remanufacturing centre r	~ U (2000,6000)
	Capacity level of recycling centre y	~ U (550,1500)
	Capacity level of disposal centre p	~ U (2000,6000)
c_a	Unit variable cost	~ U (1,10)
p_k	Selling price level per unit	~ U (200,400)
δ_{lk}	Discount percentage (% of original price(pk))	~ U (0,1)
γ_t^{lk}	Cannibalisation ratio (% of (l–1) market demand)	~ U (0,0.5)
φ_l	Recovery rate	~ U (0,0.5)
α_i	Delay (at customer node)	{0, 1}
β_i	Downgrade (at collection centre)	{0, 1}

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3.2. Numerical results

The model seems to represent well the trade-off between environmental and economic objectives; as the more prominence is given to the environmental objective function, the more careful the model is when producing products and more reverse channels are activated. The most important KPIs have been represented in Table 17.

Table 17. KPI analysis

KPI	Problem size	(Max, Mean, Min)
Obj1: Profit	P1	(263306873,209896310,138876120)
	P2	(359050400,283997022,178031152)
	P3	(708405292,551969601,336695272)
	P4	(704153210,561375466,371826292)
Obj2: Disposal	P1	(159583, 95751 ,31919)
	P2	(267193 , 160119, 52451)
	P3	(394727,236834 ,78947)
	P4	(689965,412674,138024)
Market level	P1	(5,5 (Median),4)
	P2	(5,5 (Median),4)
	P3	(5,5 (Median),4)
	P4	(5,5 (Median),4)
Reused fraction	P1	(0.74, 0.65, 0.58)
	P2	(0.74 ,0.66 , 0.59)
	P3	(0.74,0.66 ,0.60)
	P4	(0.75 ,0.66 ,0.58)
Disposed fraction	P1	(0.34, 0.29, 0.22)
	P2	(0.30 ,0.27 ,0.22)
	P3	(0.31,0.27 ,0.22)
	P4	(0.34 ,0.29 ,0.22)
Computational time	P1	19.4
	P2	150.2
	P3	383.8
	P4	366.2

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Through the application of the AUGMECON2 method, a representation of the Pareto-frontier can be proposed to decision makers. **Error! Reference source not found.** demonstrates the Pareto plot for the first set of problems with small size (P1) of different values of the objective functions, under deterministic conditions with five grid points. The two extreme scenarios are introduced by the two extreme grid points. Namely, an unregulated supply chain with no environmental constraints, with exclusive focus on profit maximisation (represented by the maximum profit value in Figure 14). In the other extreme scenario, we can assume a situation where awareness of the limited resources and planetary boundaries are the primary preoccupation of the supply chain planner; as such, profit as a KPI is entirely disregarded. In this case, the model tries to produce less products in order to avoid the disposal of goods. As shown in the figure, profit tends to decrease once the model attempts to reduce the environmental impact by sending less

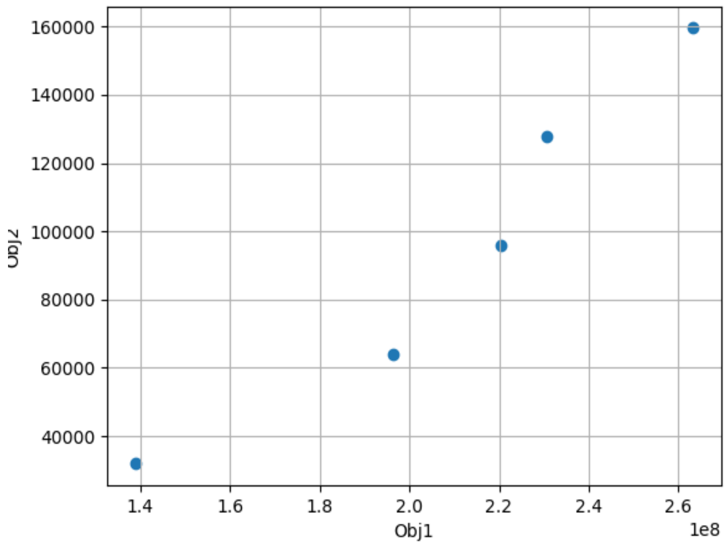

Figure 13. Pareto plot for the first set of problem

materials to disposal centres.

3.2.1. Demand satisfaction analysis

Figure 15Error! Reference source not found. displays the variation of both objective functions in each grid point (GP) in order to demonstrate the amount of satisfied demand when the focus is exclusively on either the first (Profit maximisation: GP=1.0) or on the second (Disposal minimisation: GP=5.0) objective function. As discussed above, the two extreme grid points represent the two extreme scenarios: a supply chain with no environmental constraint and, on the other hand, a situation where we acknowledge planetary boundaries and the limited nature of

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resources, discarding profit as a KPI completely. As it is observed in this figure, as the GP increases, the percentage of the total amount of satisfied demand is reduced, due to the higher prominence given to the environmental objective function that needs to be minimised. More specifically, once more prominence is given to the economic objective Z_1 (GP=1), the model tends to satisfy more

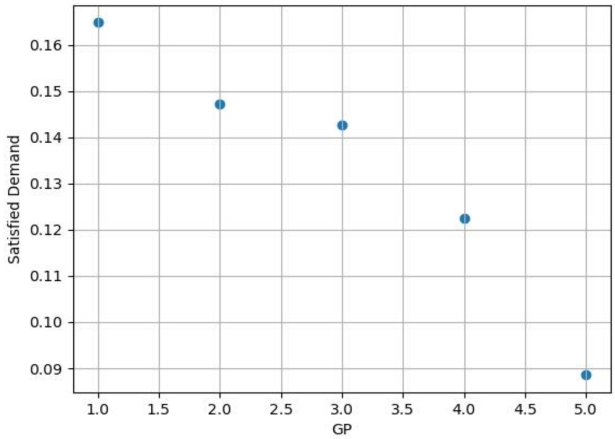

Figure 14. Satisfied demand

demand; when the environmental objective Z_2, is of more importance (GP=5), the model consciously chooses to minimise production to keep resource consumption and disposal at a minimum level.

3.2.2. Treatment Strategies

This subsection presents the response of the model to the introduction of constraints related to the different CLSC recovery options in a sequential manner. In this way, the constraints on recovery actions are activated on a one-to-one basis; in the final scenario, all recovery constraints are activated (Scenario 10), in a similar experimental setting to the one presented in the previous sub-section (P1 set of test problems, with five grid-points considered for the application of the AUGMECON2 method).

First, Reusing centres are the only strategies to be introduced in a CLSC network (Scenario 1); then, other reverse loops are added one by one to the supply network. Table 18 shows the detail of the general performance of the model for the numerical experiment using the AUGMECON2 method with five grid points; also, the average computational time required to solve P1-type problems, subject to different constraints, is reported.

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Table 18. General KPI analysis

Scenarios	KPIs / Constraints	Grid Points	Pareto solution	CPU Time
1	Max reusing	5	6	356.6
2	Min reusing	5	3	51.3
3	Max remanufacturing	5	6	88.1
4	Min remanufacturing	5	3	34.2
5	Max recycling	5	6	50.3
6	Min recycling	5	3	98
7	Reusing boundary	5	3	102.6
8	Remanufacturing boundary	5	3	33.5
9	Recycling boundary	5	3	70.6
10	All recovering constraints	5	3	84.7

As it can be seen in Table 18, by adding an upper bound to the number of returned products to be recycled, the maximum profit is obtained and consequently, the number of returned products to be disposed is at the highest level; this corresponds to the maximum value (i.e., the worst performance) of the second objective function. Accordingly, by activating all the constraints and assigning a boundary to each treatment strategy, the obtained profit is at the lowest level; similarly, the environmental objective function is minimised.

To satisfy the circular economy principles as well as to extract financial benefits from the recovery operations, Table 19 looks into the impact of each constraint on the percentage of EoL products that the model decides to reprocess. As expected, EoL products are more likely to be discarded if upper bounds are imposed to the processing capacity of recovery centres. By activating all constraints (including lower bounds), more products are reused, remanufactured and recycled in a hierarchical order (first reused, then remanufactured and finally recycled); disposals are minimised.

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Table 18. Objective functions and market level analysis

KPIs / Constraints	First Objective			Second Objective			Market levels			
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Median	Min
Max reusing	141489504	109468500	48969533	128399	61236	0	5	4.5	4	4
Min reusing	59589299	57144744	52909308	17353	7618	0	5	5	5	5
Max remanufacturing	147564585	115929812	52909308	128310	61204	0	5	4.5	4	4
Min remanufacturing	55207373	52043525	50006564	5503	3302	0	5	5	5	5
Max recycling	**147633683**	115962184	52909308	**128399**	61236	0	5	4.5	4	4
Min recycling	54183123	51099895	49196454	5503	3302	0	5	5	5	5
Reusing boundary	53918743	50868534	48969533	5503	3302	0	5	5	5	5
Remanufacturing boundary	55207373	52043525	50006564	5503	3302	0	5	5	5	5
Recycling boundary	54183123	51099895	49196454	5503	3302	0	5	5	5	5
All recovering constraints	53111687	50096720	**48235021**	5404	3242	2.27E-12	5	5	5	5

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Table 19. Effectiveness of constraints on recovery options

Constraints \ KPIs	Reused products			Remanufactured products			Recycled products			Disposed products		
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
Max reusing	28%	25%	**22%**	**32%**	26%	20%	20%	15%	13%	**34%**	21%	0%
Min reusing	**80%**	77%	74%	0%	0%	**0%**	0%	0%	**0%**	20%	9%	0%
Max remanufacturing	74%	67%	58%	0%	0%	**0%**	0%	0%	**0%**	**34%**	21%	0%
Min remanufacturing	56%	55%	53%	22%	21%	21%	0%	0%	**0%**	7%	4%	0%
Max recycling	74%	67%	58%	0%	0%	**0%**	0%	0%	**0%**	**34%**	21%	0%
Min recycling	61%	60%	58%	0%	0%	**0%**	17%	17%	16%	7%	4%	0%
Reusing boundary	30%	29%	28%	30%	28%	25%	21%	20%	19%	7%	4%	0%
Remanufacturing boundary	56%	55%	53%	22%	21%	21%	0%	0%	**0%**	7%	4%	0%
Recycling boundary	61%	60%	58%	0%	0%	**0%**	17%	17%	16%	7%	4%	0%
All recovery constraints	30%	29%	28%	26%	25%	24%	**23%**	22%	21%	7%	4%	0%

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4. Conclusions

As shown in Part I of this report, significant attention has been devoted to Closed-Loop Supply Chain design problems over the past decade. Coherently to the stated research objectives, Part I of this report has been aimed at understanding whether the current modelling approaches for CLSC problems can support the transition towards a Circular Economy at a supply chain level. In order to address this research question, the literature review section has proposed a scrutiny of 254 carefully selected papers dealing with mathematical models for the design of Closed-Loop Supply Chains.

The main findings of reviewing the academic literature have highlighted that most of the current literature in the field exhibits a disconnection between supply chain design and the founding principles of a Circular Economy, relying on reductionist sustainability measurement methods and failing to address social implications. It is important to highlight that such findings have not been highlighted by previous literature reviews.

Accordingly, Part I of this report has proposed a research agenda aimed at addressing the current literature gaps. As such, this can provide added value to researchers in the field, describing a clear set of priorities for future investigations. While the academic literature has developed an abundant stream of work related to the mathematical models for Closed-Loop Supply chain design problems, such modelling proposals tend to be over-specific and lack generality.

Consequently, in Part II of this report, a mathematical model aimed at designing a CLSC network has been proposed, by addressing some of the main gaps identified in the current literature. Specifically, efforts have been made to introduce a compact mathematical formulation for a CLSC design problem, based on CE principles, such as the need to minimise waste throughout the supply chain and the activation of markets for reused and remanufactured products. An AUGMECON2 algorithm has been also implemented in order to provide a solution to the proposed bi-objective programming model; in this report, also some preliminary results have been presented. In the next steps of this research, the computational experiments will be significantly expanded; also, the possibility of including further objective functions and constraints, based on social objectives related to the implementation of CE practices, will be evaluated.

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Appendix.

This appendix collects some tables derived from the literature analysis presented in Part I, which have been referred directly in the text.

Table A1. List of journals in the "Other" category of 4 and below 4 (based on Table 2)

Journal	NP
Scientia Iranica	4
Journal of Manufacturing Systems	4
Journal of Industrial and Production Engineering	4
Omega (United Kingdom)	3
Computers and Operations Research	3
Human and Ecological Risk Assessment	3
International Journal of Industrial Engineering Computations	3
Journal of Remanufacturing	3
Annals of Operations Research	3
Transportation Science	3
International Journal of Sustainable Engineering	3
Journal of Intelligent and Fuzzy Systems	3
Expert Systems with Applications	3
Journal of Industrial Engineering International	2
RAIRO - Operations Research	2
Logistics Research	2
International Journal of Fuzzy Systems	2
Uncertain Supply Chain Management	2
Fuzzy Sets and Systems	2
Journal of Uncertain Systems	2
International Journal of Management Science and Engineering Management	2
International Journal of Applied Decision Sciences	2
International Journal of Operational Research	2
Transportation Research Part D: Transport and Environment	2
IFAC-PapersOnLine	2
Journal of Industrial Engineering and Management	2
Knowledge-Based Systems	2
Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	1
Assembly Automation	1
International Journal of Services and Operations Management	1
International Journal of Systems Science: Operations and Logistics	1
PLoS ONE	1
International Transactions in Operational Research	1
Robotics and Computer-Integrated Manufacturing	1

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Iranian Journal of Fuzzy Systems	1
Waste Management	1
Journal of Advanced Manufacturing Systems	1
DYNA (Colombia)	1
Journal of Business Economics	1
Soft Computing	1
Journal of Central South University of Technology (English Edition)	1
Computational and Mathematical Organization Theory	1
Advances in Information Sciences and Service Sciences	1
EURO Journal on Transportation and Logistics	1
Journal of Computer and Systems Sciences International	1
International Journal of Applied Engineering Research	1
Journal of Enterprise Information Management	1
Journal of Advances in Management Research	1
Advanced Engineering Informatics	1
Physica A: Statistical Mechanics and its Applications	1
International Journal of Information Systems and Supply Chain Management	1
International Journal of Industrial and Systems Engineering	1
Computational Intelligence	1
Chaos, Solitons and Fractals	1
Indian Journal of Science and Technology	1
OR Spectrum	1
Journal of Intelligent Manufacturing	1
Production and Operations Management	1
Journal of Japan Industrial Management Association	1
Resources, Conservation and Recycling	1
Industrial Engineering and Management Systems	1
Engineering Optimization	1
Journal of Modelling in Management	1
Technological and Economic Development of Economy	1
Production Planning and Control	1
Advances in Production Engineering And Management	1
Asia-Pacific Journal of Operational Research	1
IIE Transactions (Institute of Industrial Engineers)	1
Journal of Transport Geography	1
AIChE Journal	1
International Journal of Computer Applications in Technology	1
Decision Science Letters	1
International Journal of Innovative Computing, Information and Control	1
IISE Transactions	1

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International Journal of Computational Intelligence Systems	1
Progress in Industrial Ecology	1
International Journal of Industrial Engineering: Theory Applications and Practice	1
Jordan Journal of Mechanical and Industrial Engineering	1
Mathematical Problems in Engineering	1
International Journal of Business Analytics	1
Mediterranean Journal of Social Sciences	1
Industrial and Engineering Chemistry Research	1
Naval Research Logistics	1
International Journal of Retail and Distribution Management	1
Neural Computing and Applications	1
International Journal of Systems Science	1
Computer Aided Chemical Engineering	1
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	1
Journal of Optimization in Industrial Engineering	1

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