STRATEGIC PLANNING OF CIRCULAR SUPPLY CHAINS WITH MULTIPLE DOWNGRADED MARKET LEVELS:

A METHODOLOGICAL PROPOSAL

By:

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Azar MahmoumGonbadi

The University of Sheffield, 2023

This thesis is dedicated to

my mother

and

all Women in Iran

DECLARATION

I, Azar MahmoumGonbadi, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not previously been presented for an award at this, or any other, university.

RESEARCH DISSEMINATION

All publications arising from the thesis are acknowledged in this section as follows:

JOURNAL PAPERS

● Azar MahmoumGonbadi, Andrea Genovese, Antonino Sgalambro, (2021), "Closed-loop supply chain design for the transition towards a circular economy: A systematic literature review of methods, applications and current gaps", *Journal of Cleaner Production*. DOI: https://doi.org/10.1016/j.jclepro.2021.129101.

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CONFERENCE PAPERS

- Azar MahmoumGonbadi, Andrea Genovese, Antonino Sgalambro, (2022), "Mathematical models for the strategic planning of multi-market closed-loop supply chains", *Circular Economy Research Club (CERCL), The University of Sheffield, Sheffield, UK.*
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Technical Reports (Deliverables)

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• Azar MahmoumGonbadi, Andrea Genovese, Antonino Sgalambro, (2022), “Mathematical modelling toolkit for solving decision-making problems for the establishment of circular supply chains”.

http://www.retrace-itn.eu/wp-content/uploads/2022/10/ReTraCE_D1.6.pdf

• Azar MahmoumGonbadi, Tommaso Calzolari, Andrea Genovese, (2022), “Circular Economy indicators promoted by think thanks–A case study from material processing industry”

ABSTRACT

Recent legislation has recognized the importance of adopting Circular Economy (CE) principles in supply chain (SC) restructuring. The primary objective is to create circular supply chains (CSCs) that effectively reintegrate end-of-life (EOL) products into production networks through processes such as reusing, remanufacturing, and recycling. This paradigm shift toward circularity aims to enhance resource efficiency, extend product lifecycle, and minimise waste, thereby aligning firms with sustainable practices while providing them with a competitive advantage.

In line with the goals of the CE, this study focuses on the design and optimisation of strategic decisions within a circular supply chain (CSC). To achieve this aim, a bi-objective mixed-integer linear programming (MILP) model is developed. This model represents a significant contribution as it offers a compact and generalized formulation for dealing with CSC design problems.

The proposed MILP model encompasses several key decision variables and considerations. It determines the optimal number of downgraded market levels to be activated, the location of forward and treatment facilities as well as the optimal product flow within the CSC. Furthermore, the model takes into account the cannibalisation effects associated with the demand for both new and recovered products, ensuring a comprehensive analysis of the system dynamics.

To solve the complex mathematical model, the augmented epsilon-constraint (AUGMECON2) method is employed. The utilisation of this method enables decision-makers to obtain practical solutions within reasonable time frames. The computational results obtained from applying the MILP model illustrate its encouraging potential and effectiveness in dealing with strategic decision-making problems within CSCs.

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CE – Circular Economy

CSC – Circular Supply Chain

SC – Supply Chain

SCM – Supply Chain Management

MILP – Mixed Integer Linear Programming

GSC – Green Supply Chain

SSC – Sustainable Supply Chain

CLSC – Closed Loop Supply Chain

RL – Reverse Logistics

BM – Business Models

EOL – End of Life

BOP – Bottom of Pyramid

CHAPTER 1: INTRODUCTION

Supply chain (SC) design activities involve the determination of the most efficient and effective way to design and optimise the flow of products across facilities (Zandkarimkhani et al., 2020). Mathematical modelling plays a key role in this process, as it allows managers to simulate different scenarios and evaluate the impact of various decisions on the overall performance of the SC. Within this context, enabling novel consumption and production approaches is indispensable to moving towards a more sustainable economic model (Rezaei & Kheirkhah, 2018a). In this regard, companies are experiencing an urgent need to integrate the Circular Economy (CE) principles into their supply networks due to the increased environmental awareness from customers as well as more stringent governmental legislation. According to the European Commission (2015), in a CE, materials and products are maintained within production systems through a sequence of feedback loops (EMF, 2015), reducing the necessity for using virgin raw materials and the generation of waste (Genovese et al., 2017).

Hence, both top-down legislation from governments and supra-national bodies, and bottom-up innovations from industrial organisations are crucial to accelerate the transition towards a CE (Bressanelli et al., 2019). As a consequence, appropriate SC design and planning is required in order to establish building blocks towards the implementation of CE practices (Genovese et al., 2017b). In particular, firms can take advantage of different types of SC configurations for implementing CE practices, namely:

- **Open-loop SC design:** Where third parties are accountable for recovery of End-of-Life (EOL) products (Genovese et al., 2017b); For instance, EOL tires can be re-utilised by the cement industry by recycling and turning them into rubber asphalt (Nag et al., 2021).
- **Closed-loop SC design:** In which both forward and reverse flows are managed centrally by the original manufacturer (Rezapour et al., 2015), and returned products are reversed back to the original firm who manufactured them.
- **Circular SC design:** In which the closed-loop paradigm is extended, in order to go beyond simple reverse logistics objectives, in order to achieve an harmonious development model, taking into account physical boundaries in terms of resources and energy and

social wellbeing, promoting both economic performance and environmental preservation in a harmonious manner (Murray et al., 2017).

While Circular Supply Chains (CSCs) and Closed-Loop Supply Chains (CLSCs) are similar in their focus on reducing waste and promoting sustainability, they differ in their approach to achieving these goals. The main difference is in the wider adoption of CE principles. The purpose of a CLSC is mainly to recover EOL products and materials. In contrast, the purpose of a CSC is to consider wider CE principles to create diverse loops of slowing, closing, narrowing, reducing, and intensifying as illustrated in the right circle of Figure 1. A CSC tends to minimise the inputs of resources (virgin raw materials), displacing their usage through the recovery of EOL products, as well as the generation of wastes leaking into the environment through feedback loops.

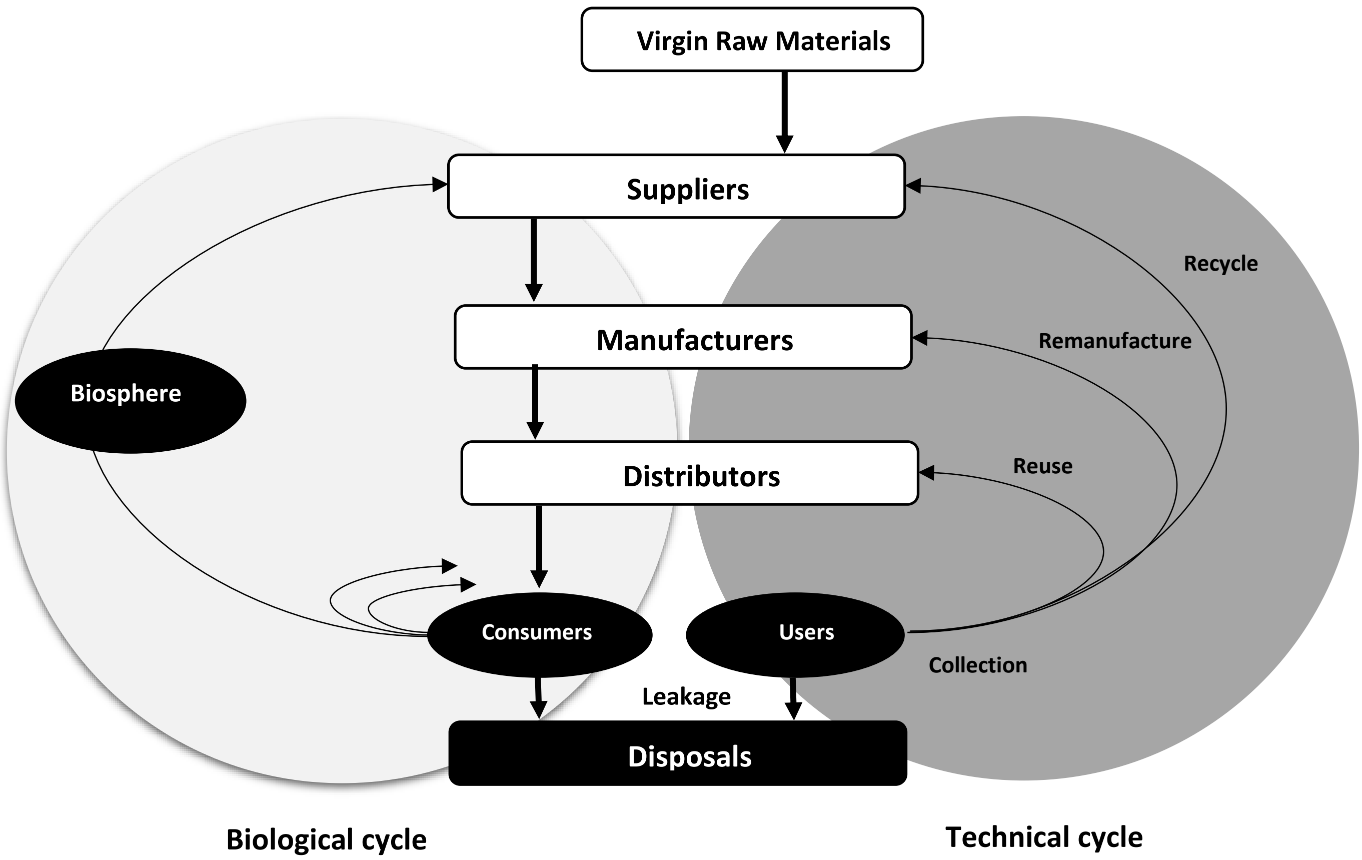

Figure 1. The Circular Supply Chains-Adopted from the Ellen MacArthur Foundation

While a very broad range of scientific contributions is addressing CSC problems, the research on strategic CSC design problems through optimisation-based tools still lacks tailored optimisation approaches to secure actionable decision-making support in the presence of specific CE objectives. In particular, there is no contribution considering introducing and optimising the number of downgraded market levels while designing a CSC model. This turns out to be a significant gap, as balancing and integrating CE principles whilst proposing recovered products in the network can potentially align waste reduction with profitability goals.

Despite the fact that CSCs are significant building blocks in the transition towards a CE in SC design problems, such networks have been overlooked in optimisation studies. Hence, in this research, a bi-objective CSC model is considered by introducing the concept of multiple downgraded market levels, which refers to the different markets where a product can be sold after its initial use. For instance, a product may be sold as a primary product initially; and after its initial use, it can be downgraded and sold at a reduced price as a secondary product in a secondary market. After further use, it can be downgraded again and sold as a tertiary product in yet another market. Each downgraded market level represents a different market where the product can be sold, allowing for multiple cycles of use and reuse before the product ultimately reaches its end of life and is disposed of (this is called "intensifying" use). Having multiple downgraded market levels is important in a CSC because it can maximise the value extracted from products and minimises waste, contributing to a more sustainable and environmentally friendly approach to production and consumption.

More specifically, there are several reasons that highlight the necessity of having multiple downgraded market levels in a CSC, namely:

- ***Maximising Resource Recovery:*** When a product reaches the end of its useful life, it can be recovered and processed multiple times. Each time a product is processed, it loses some of its value and quality, but it also means that more resources are being recovered and less waste is being generated, provided that there is demand for such recovered products. This can help reduce the amount of virgin materials needed, which is a key goal of CE principles and therefore increases the displacement ratio across the whole supply network. As a result, by recovering and processing products, a CSC can reduce its environmental impact.

- ***Meeting Different Customer Needs:*** Different customers have different needs and preferences, and by offering multiple downgraded market levels, a CSC can hugely contribute to the social dimension of sustainability. Some customers may be willing to pay more for a higher-quality product, while others may be more interested in a lower-priced product that has been recovered and processed. By offering a range of products, a company can capture more market share and increase its overall revenue. The Bottom of the Pyramid (BOP) market refers to the socio-economic segment comprised of the poorest disadvantaged individuals (Jun et al., 2013). An example of the BOP market (Figure 2) could be rural or low-income urban populations in developing countries, who may have limited financial resources and access to basic goods and services. These consumers may prioritise affordability and basic functionality over brand or product quality and may be willing to purchase downgraded products at a lower price point. A company that offers such products tailored to the BOP market can cater to these consumers' needs while also contributing to the social dimension of sustainability.

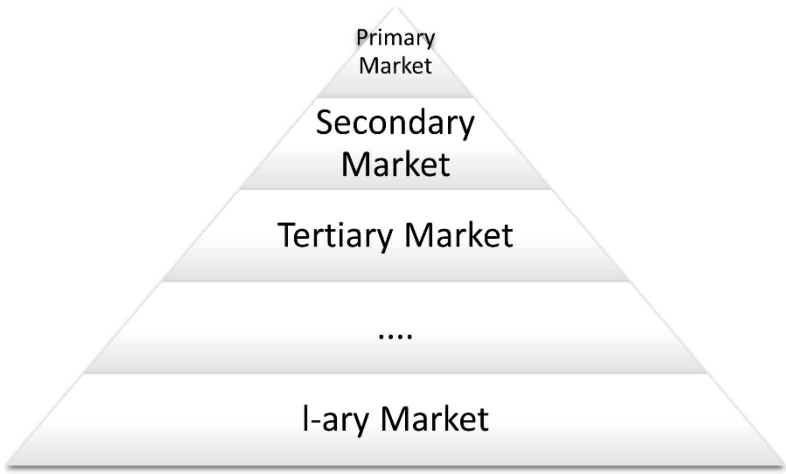

Figure 2. Market Pyramid

One of the important phenomena that is more likely to happen in such a CSC is the fact that the difference between new and recovered product prices might cause a migration of some consumers from the purchase of new products to recovered ones; this phenomenon is called the "cannibalisation effect". In other words, cannibalisation is perceived as the demand leakage that leads to the loss of sale of one product sale due to another one, where downgraded products can potentially cannibalise sales of higher-quality products. Hence, evaluating the impact of recovered products sale on the new products is essential and needs to be investigated.

As there is a lack of attention given to these features while supporting CSC design, this research aims to fill this gap by introducing a comprehensive mixed-integer linear programming (MILP) model to design a CSC to help businesses accelerate toward the implementation of CE. The bi-objective model copes concurrently with profit maximisation and waste minimisation and supports CSC design including various recovery options as represented in the technical cycle of **Error! Reference source not found.**. It also recognizes the importance of evaluating the impact of recovered product sales on new product sales in CSCs. By doing so, it takes the potential cannibalisation effect into account and helps decision-makers make informed decisions on the allocation of resources in their SCs. To this end, the model proposes a novel approach to optimise the facility locations, transportation flow and provide the optimal number of downgraded market levels considering all the possible scenarios. This enables efficient resource allocation and ensures that customer demands are met in the most cost-effective manner.

1.1. Research aims and objectives

This research aims to address the gap in the literature regarding the design and optimisation of strategic decisions in CSC by introducing the concept of multiple downgraded market levels. The objectives of this study are as follows:

1. Develop a comprehensive mixed-integer linear programming (MILP) model for designing a CSC that integrates CE principles and supports strategic decision-making. The model should simultaneously optimise profit maximisation and waste minimisation, considering various recovery options and the potential cannibalisation effect.
2. Investigate the impact of multiple downgraded market levels in a CSC. Evaluate the trade-offs between objective functions to identify the optimal number of downgraded market levels.

3. Optimise the location of facilities and transportation flows within a CSC to minimise operational costs and environmental impacts. Consider factors such as facility capacities, various recovery options and downgraded market levels.
4. Provide decision-makers with actionable insights and decision support tools for efficient resource allocation and strategic decision-making in CSCs.
5. Evaluate the performance and effectiveness of the proposed MILP model through computational experiments, demonstrating its applicability and potential for real-world implementation.

By achieving these aims and objectives, this research aims to contribute to the field of CSC design and optimisation by providing decision-makers with a robust framework and practical guidelines for designing and managing CSCs. Ultimately, the research aims to promote sustainable practices, enhance resource efficiency, and reduce waste generation within supply chains, thereby fostering the transition towards a CE.

1.2. General Overview of the Developed Model

This section aims to provide readers with a concise yet comprehensive overview of the developed model, including its underlying fundamentals, main features, and the type of network it addresses.

The proposed mathematical model addresses the complex decision-making process involved in strategic planning for CSCs. It is designed as a deterministic model, assuming the availability of dependable parameters.

The bi-objective MILP model seeks to maximise the total profit, serving as a key motivation for companies to prioritise CE practices and embed them into their operations. It also aims to minimise the total number of discarded products, thereby enhancing the overall sustainability and CE metrics of the CSC. Achieving these objectives requires optimising decisions related to facility locations, the number of activated downgraded market levels, and transportation quantities. The model also considers distinct recovery options such as reusing, remanufacturing, and recycling while accounting for the cannibalisation effect of downgraded products and promoting full displacement of raw materials.

The proposed approach is formulated through a multi-product, multi-period, and multiple downgraded market level Mixed-Integer Linear Programming (MILP) network design model. To solve this complex MILP model, the improved version of the augmented epsilon-constraint (AUGMECON2) method is employed. The AUGMECON2 method is implemented using the Python programming language, and the "*docplex*" libraries are utilised to iteratively solve the mixed-integer programming models by calling the IBM ILOG CPLEX solver version 12.6.

In general, the developed bi-objective model provides a robust framework for strategic planning in CSCs, by optimising decisions related to facility locations, transportation flows, and downgraded market levels. The model facilitates the maximisation of profit, improvement of sustainability and CE-based objective function by considering various recovery options.

1.3. Thesis organisation

This section provides an overview of the organization and structure of the thesis. It outlines the main chapters and sections, highlighting the key content and research contributions presented in each.

This chapter provided an overview of the research conducted. It begins by stating the research aims and objectives, outlining the specific goals of the study. A general overview of the developed model is then presented, highlighting the main features and fundamentals of the model.

Next chapter offers an overview of previous literature reviews conducted on closed-loop supply chains (CLSC) and reverse logistics (RLs). The research methodology employed for the systematic literature review (SLR) is discussed, including source identification, selection, evaluation, and data analysis. The discussion section highlights the research agenda for CLSC research, emphasizing the contribution of this thesis.

Chapter 3 delves into the research methodology employed in this study. It provides an overview of the research background and describes the problem under study. The problem description is presented, highlighting the specific challenges and issues addressed in the research. The research approach and philosophical review are discussed, explaining the chosen approach and the underlying philosophical considerations. The research framework is presented, outlining the different phases involved in the study, including Phase 1, Phase 2, and Phase 3.

Chapter 4 focuses on the mathematical formulation of the proposed CSC problem. The bi-objective mathematical CSC problem is explained, along with the objective functions and constraints of the generic optimisation model as well as the adopted solution method are thoroughly explained in this chapter.

Chapter 5 presents the experimental evaluation conducted as part of this research, followed by a description of the data generation process. The findings and implications of the experiments are discussed.

Chapter 6 provides the findings of the developed model, providing insights into the robustness and stability of the model.

Chapter 7 serves as the final chapter of the thesis. The chapter engages in a detailed discussion of the research, analysing and interpreting the findings in light of the research objectives. The contributions of the research are outlined, encompassing contributions to the area of study, model development, and practical implications. The chapter concludes with a discussion of the limitations of the research and suggestions for future research directions.

CHAPTER 2: CLOSED-LOOP SUPPLY CHAIN DESIGN FOR THE TRANSITION TOWARDS A CIRCULAR ECONOMY: A SYSTEMATIC LITERATURE REVIEW OF METHODS, APPLICATIONS AND CURRENT GAPS[1]

2.1. Introduction

This chapter performs a systematic literature review (SLR), aiming at assessing how the current CLSC design approaches can support the transition towards a CE at a SC 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.

2.2. A look at previous literature reviews

The full list of relevant literature review papers, along with their 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 (BMs) 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.

[1] This chapter is published as a paper in Journal of Cleaner Production (JCP); https://doi.org/10.1016/j.jclepro.2021.129101

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.

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.

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 (SSCs) 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.

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)
RL & CLSC	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
	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
	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

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 SC challenges; Bressanelli et al. (2019) identified and categorise 24 challenges that may hinder the 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 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 CE 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.

2.3. Systematic Literature Review – Methodological Notes

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 SCM fields of study (Govindan et al., 2015; Jayasinghe et al., 2019; Jena & 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.

2.3.1. 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*")
- 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 3. 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.

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

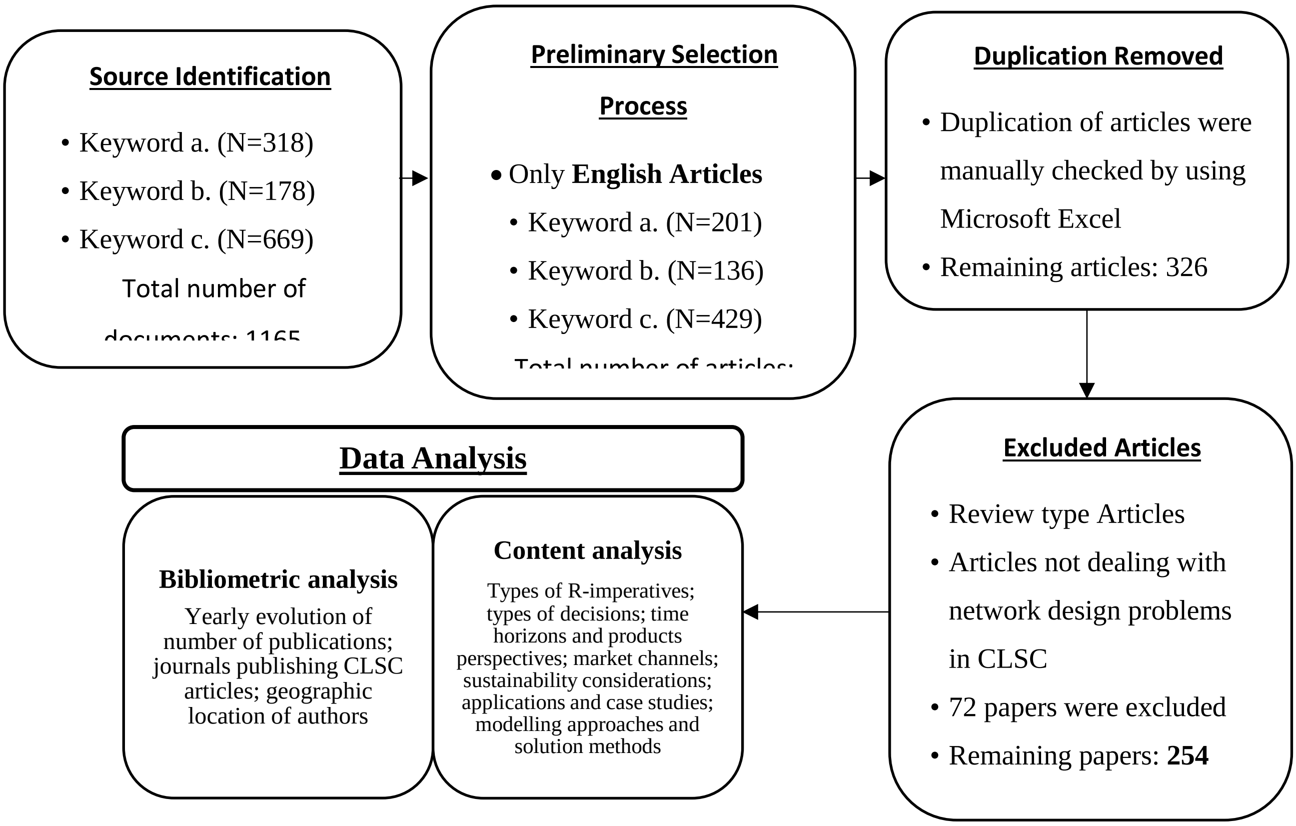

Figure 3. Article search and evaluation process

2.3.2. 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 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 (J. Zhang & Chmielewski, 2017) or local open- and closed-loop manipulation of multi-agent networks (Sahabandu et al., 2019) which are not concerning with SC 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.

2.3.3. 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 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.

2.3.4. 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.

2.4. 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.

2.4.1. General Bibliometric Analysis

Figure 4 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.

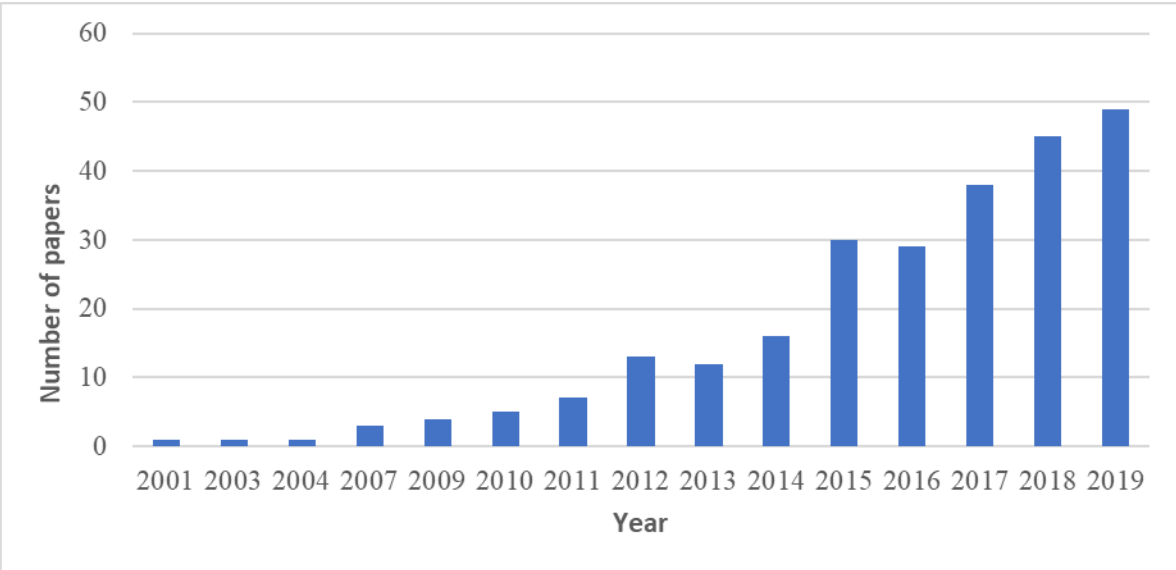

Figure 4. Number of publications across the period under investigation

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 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 (NP = Number of Publications)

Journal	NP
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 5 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 CE 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.

Figure 5. 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 CE agenda.

2.4.2. 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 2). 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.

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 (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) (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 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 SCs, rather than designing new production units which are fully inspired by a CE paradigm.

A general CLSC structure is given in Figure 6, 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.

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 & Geraeli, 2019)**; Laptop** (Darbari et al., 2019); **Inkjet printers**(Govindan et al., 2017); **Consumer goods** (L. J. Zeballos et al., 2018); **Copier industry** (Nagasawa et al., 2017a); **Glass** (Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Salema et al., 2010); **Vehicles**(Mora et al., 2014); **Mushroom**(Banasik et al., 2017); **Home appliance** (W. 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; Ghomi-Avili et al., 2019; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; Jabbarzadeh et al., 2018; Pourjavad & Mayorga, 2019a; Salema et al., 2010; L. J. Zeballos et al., 2012); **Oil and gas**(Montagna & Cafaro, 2019; Saedinia et al., 2019); **Paper**(Ahranjani et al., 2018); **Consumer goods**(M. A. Kalaitzidou et al., 2015; L. J. Zeballos et al., 2018); **Tire**(Ebrahimi, 2018; Subulan, Taşan, & Baykasoğlu, 2015); **Household appliance**(Faccio et al., 2011; Keshavarz 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**(Hamidieh et al., 2018); **Gold**(Zohal & Soleimani, 2016a); **Consumer goods** (M. A. Kalaitzidou et al., 2015); **Hospital furniture** (Soleimani & Kannan, 2015a); **Geyser**(Garg et al., 2015); **Tire**(Pedram et al., 2017); **Plastic water cane** (Soleimani et al., 2016); **Copier industry**(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**(Prakash et al., 2017b)**; Copier industry** (Krikke, 2011); **Vehicles** (Cruz-Rivera and Ertel, 2009).
Remanufacturing	117	**Wire and cable**(Mardan et al., 2019b); **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** (A. 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; Krikke, 2011; Nagasawa et al., 2017b; Steinke & Fischer, 2016; Talaei et al., 2016); **Gold**(Zohal & Soleimani, 2016a); **Construction machinery**(Yi et al., 2016); **Consumer goods**(M. A. M. A. Kalaitzidou et al., 2015); **Iron and steel**(Vahdani, 2015; Vahdani & Mohammadi, 2015); **Cell phone** (Khatami et al., 2015); **Tire** (S. H. Amin et al., 2017; Pedram et al., 2017; Subulan, Taşan, & Baykasoğlu, 2015); **Automotive spare parts**(Rezapour et al., 2015); **Hospital Furniture**(Soleimani & Kannan, 2015a); **Paper**(Fleischmann et al., 2001; Pazhani et al., 2013); **Automotive** (Rezapour et al., 2015; Üster et al., 2007); **Plastic water cane**(Soleimani et al., 2016); **Furniture**(Accorsi et al., 2015);**Bread**(Mirakhorli, 2014); **Refrigerator**(Krikke et al., 2003; Y. Wang et al., 2012); **Vehicles**(Cruz-Rivera & Ertel, 2009; Mora et al., 2014); **Information and communications technology (ICT) industry**(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**(Vahdani & Mohammadi, 2015); **Home appliance** (W. Chen et al., 2015); **Bottles** (Lee, Jeong-Eun ; Lee, 2011)**; Refrigerator**(Krikke et al., 2003); **Tire** (Pedram et al., 2017; Subulan, Taşan, & Baykasoğlu, 2015).
Dismantling	43	**Laptop**(Darbari et al., 2019); **Automotive**(Özceylan et al., 2017a); **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**(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; L. J. Zeballos et al., 2012); **Oil and gas**(Saedinia et al., 2019)**; Laptop**(Darbari et al., 2019; Hamidieh et al., 2018); **Food Industry** (A. Abdi et al., 2019); **Paper**(Ahranjani et al., 2018; Fleischmann et al., 2001; Pazhani et al., 2013; Safaei et al., 2017; 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; Subulan, Taşan, & Baykasoğlu, 2015); **Filter**(Ghomi-Avili et al., 2018a); **Consumer goods**(M. A. M. A. Kalaitzidou et al., 2015; L. J. L. J. L. J. Zeballos et al., 2018); **Electronic products**(Lu et al., 2019; L. Ma & Liu, 2017; Subramanian et al., 2013); **Automotive**(Özceylan et al., 2017a); **Inkjet printers**(Govindan et al., 2017); **Copier industry**(Fleischmann et al., 2001; Krikke, 2011; Nagasawa et al., 2017a); **Gold**(Zohal & Soleimani, 2016a); **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; Subulan, Baykasoɫlu, et al., 2015; Subulan, Taşan, & Baykasoɫlu, 2015); **Iron and steel**(Vahdani, 2015; Vahdani et al., 2013); **Hospital Furniture**(Soleimani & Kannan, 2015a); **Geyser**(Garg et al., 2015); **Household appliance**(W. Chen et al., 2015; Keshavarz Ghorabaee et al., 2017); **Plastic water cans** (Soleimani et al., 2016);**Furniture**(Accorsi et al., 2015); **Vehicles** (Cruz-Rivera & Ertel, 2009; Mora et al., 2014); **Refrigerators** (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** (Özceylan et al., 2017a); **Vehicles**(Cruz-Rivera and Ertel, 2009; Mora et al., 2014)

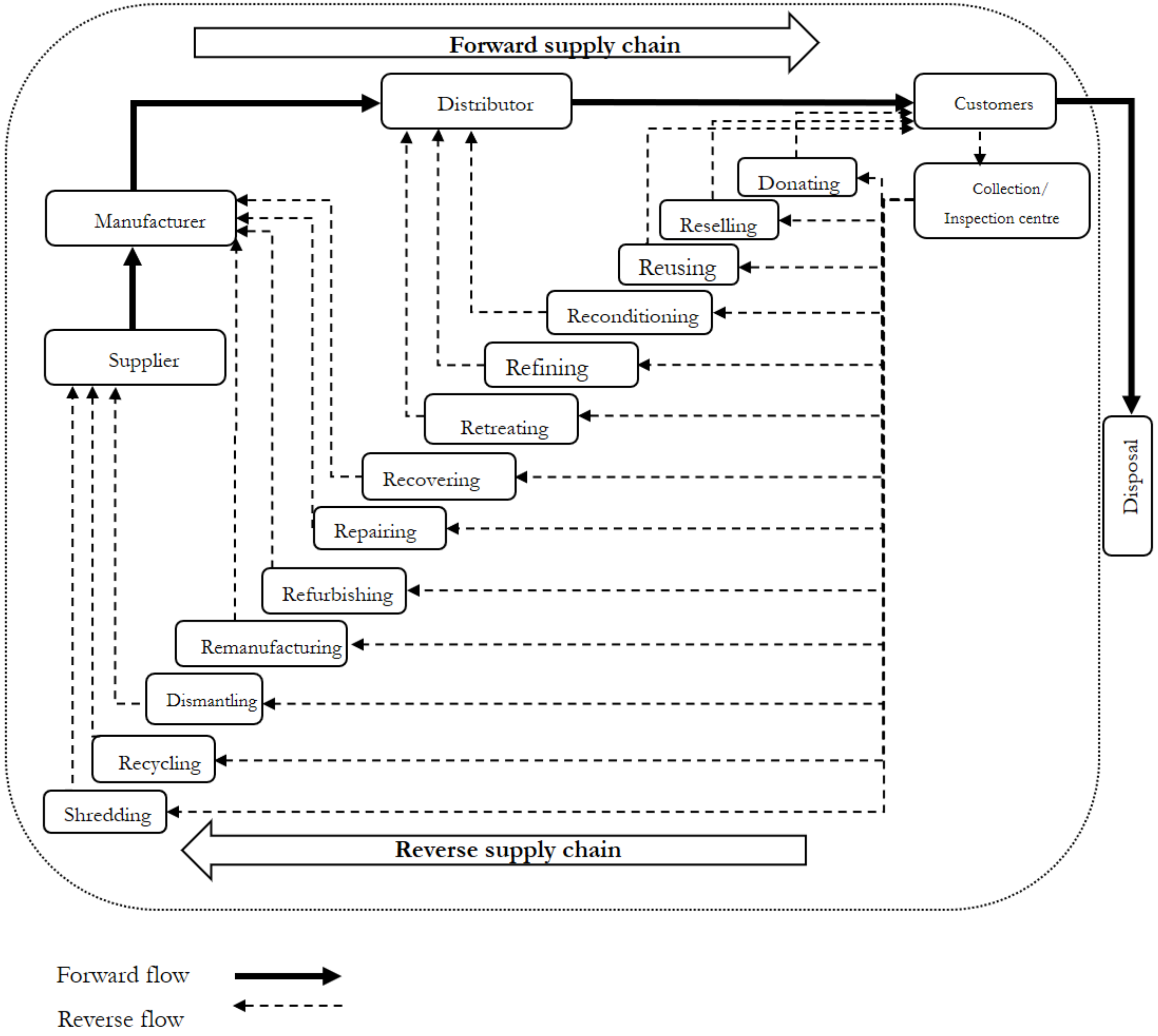

Figure 6. General layout of a closed-loop supply chain

2.4.3. 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 (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.

Table 4. Types and examples of decision levels

Decision Level	Decision Type	Examples
Strategic decisions (N=74)	Number of Facilities	(Hamidieh & Fazli-Khalaf, 2017; Özkir & Başligil, 2012; Prakash et al., 2017a)
	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; L. L. Zhen et al., 2019)
	Facility scale	(Liu et al., 2019; Montagna & Cafaro, 2019; L. Zhen et al., 2019)
	Technology type	(Farrokh et al., 2018; Sadeghi Rad & Nahavandi, 2018; Subulan, Taşan, & Baykasoğlu, 2015)
	Transportation channels	(Ahranjani et al., 2018; Atabaki et al., 2019; Zohal & Soleimani, 2016a)
	Product design	(Das & Chowdhury, 2012; 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	(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	(Çalık et al., 2017; Ghomi-Avili et al., 2019; Mardan et al., 2019a)
	Pricing decisions	(Kaya & Urek, 2016; Litvinchev et al., 2014; Taleizadeh et al., 2019)
	Discount level	(Darestani & Hemmati, 2019; Hajiaghaei-Keshteli & Fathollahi Fard, 2019; 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; Salema et al., 2009; L. J. Zeballos et al., 2016)
	Vehicle selection	(Çalık et al., 2018; Liu et al., 2018; RajKumar & Satheesh Kumar, 2015)
	Fleet composition	(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)
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)

2.4.4. 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; L. L. Zhen 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 SCs 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 7.

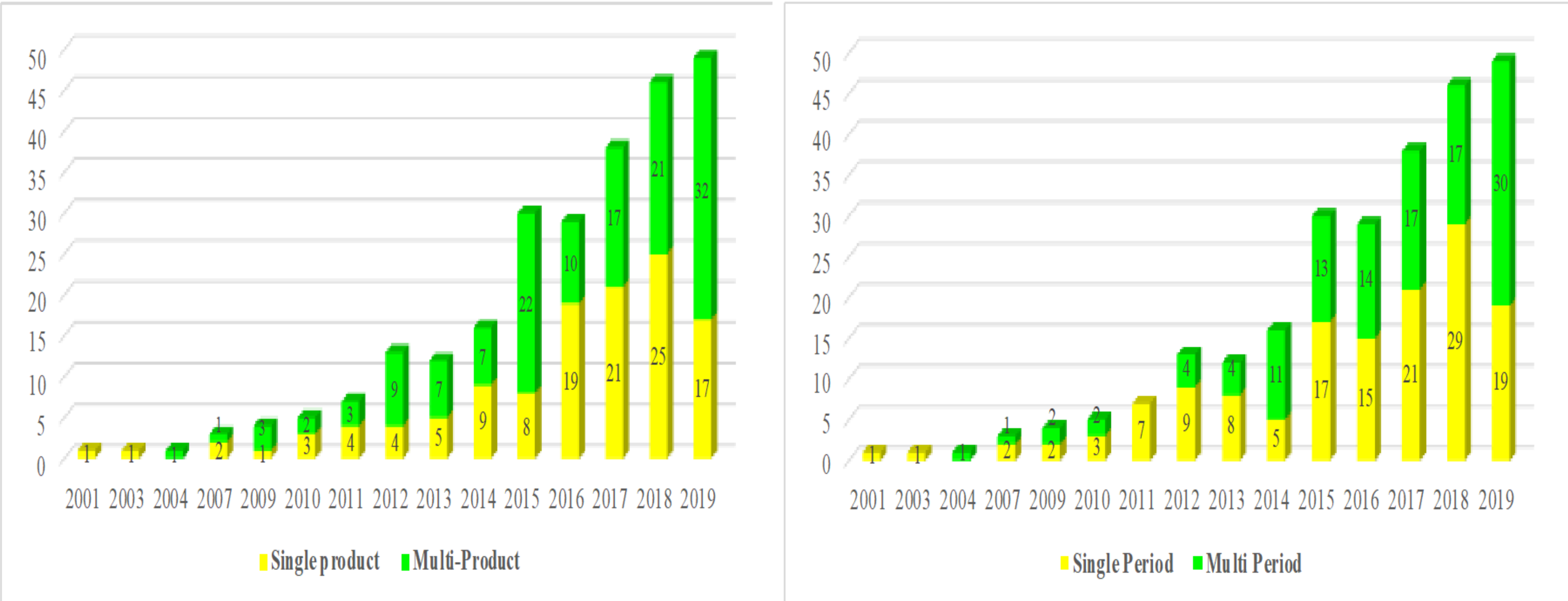

Figure 7. Analysis of products and periods in the mathematical modelling approaches

2.4.5. 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.

2.4.6. 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 8 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 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 SC 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 9 (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 9 (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 indicators, disposal rate and last but not least Life Cycle Analysis measures are less commonly employed. In the light of the transition to a CE, 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 SC 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 9, 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 SC (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 SC cost; 83 out of 130 articles are only dealing with cost issues (Sherafati and Bashiri, 2016; Torabi et al., 2016); the remaining ones are mainly related to maximising net profits (Atabaki et al., 2019; H. Ma & Li, 2018).

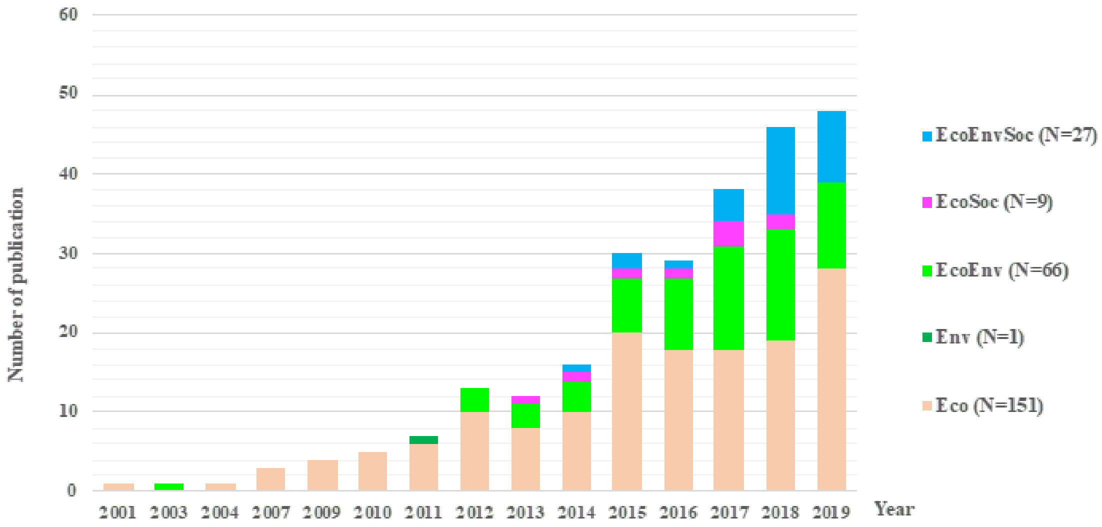

Figure 8. Focus on TBL sustainability dimensions and yearly evolution

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; 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.**.

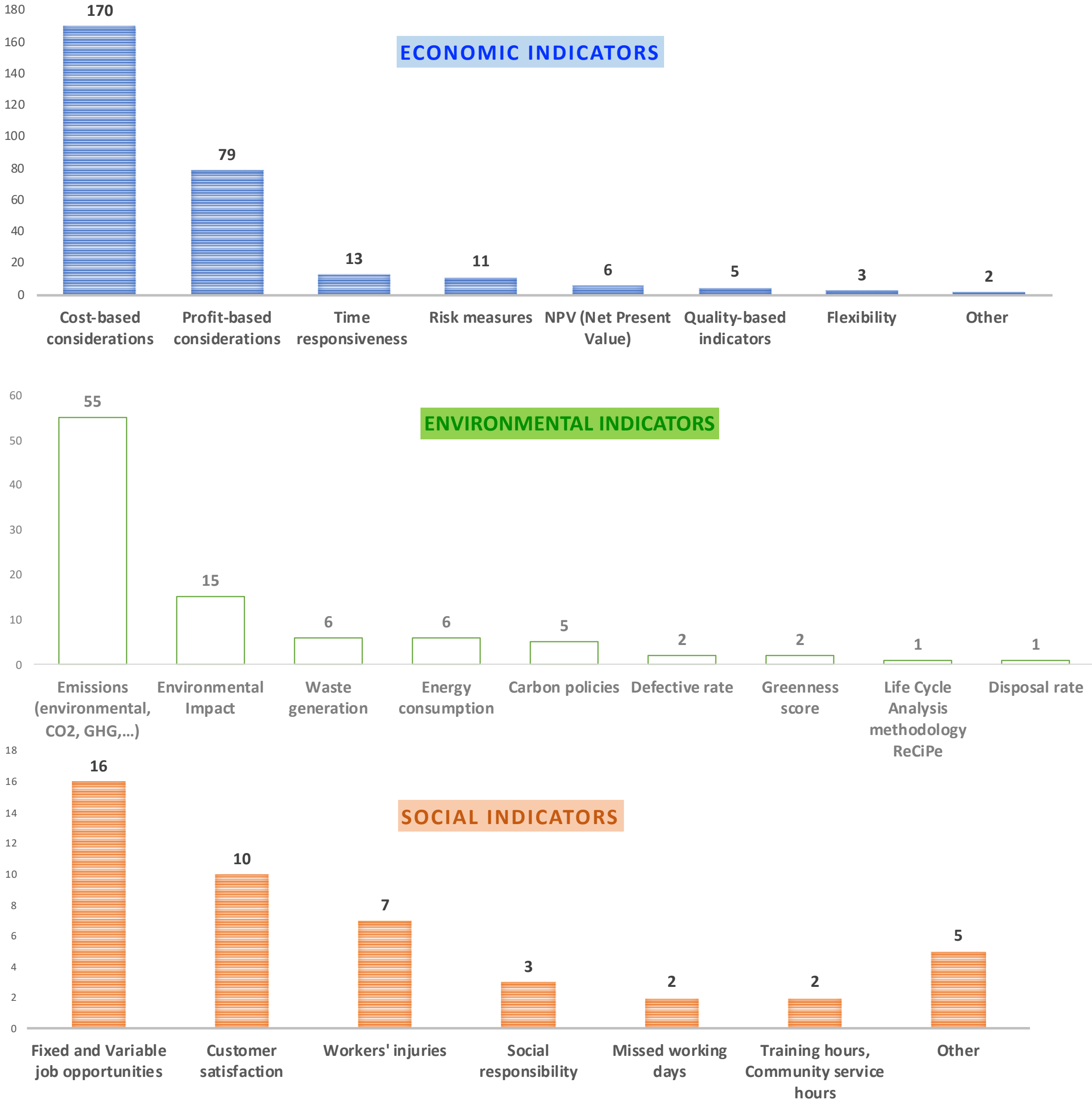

Figure 9. Economic, Environmental and Social Indicators

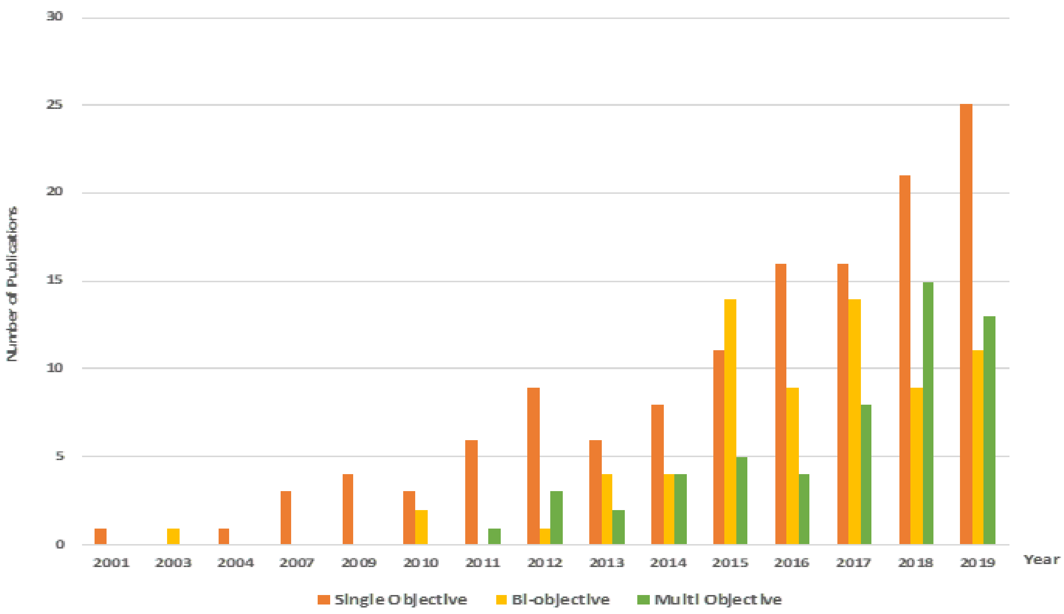

Figure 10. Yearly evolution of objective functions

2.4.7. 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.

Error! Reference source not found. 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 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.

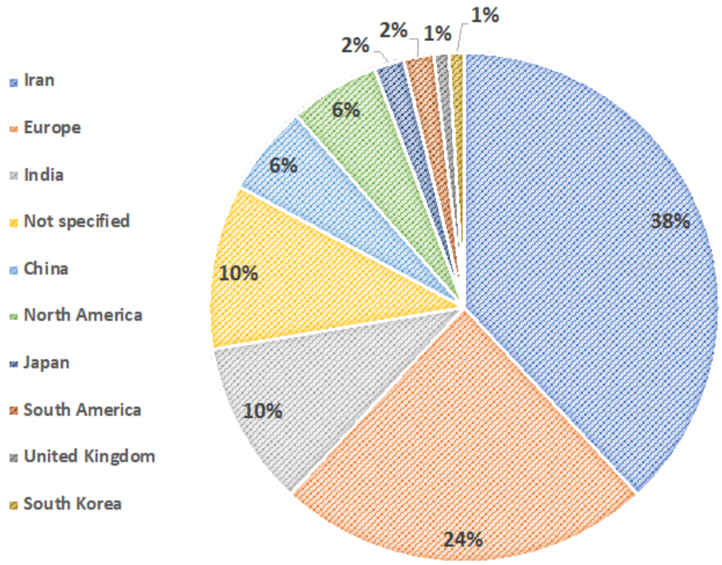

Figure 11. Case Study Locations

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
Construction & Engineering	1
Energy Equipment & Services	1

IT Services	1
Generic Machinery	1
Media	1
Textiles, Apparel & Luxury Goods	1

2.4.8. Modelling approaches and solution techniques

Existing CLSC models can be classified into deterministic and non-deterministic ones (**Error! Reference source not found.**). Non-deterministic models consider the uncertainty associated with some parameters such as demand or return quantity (Akçcal and Çetinkaya, 2011).

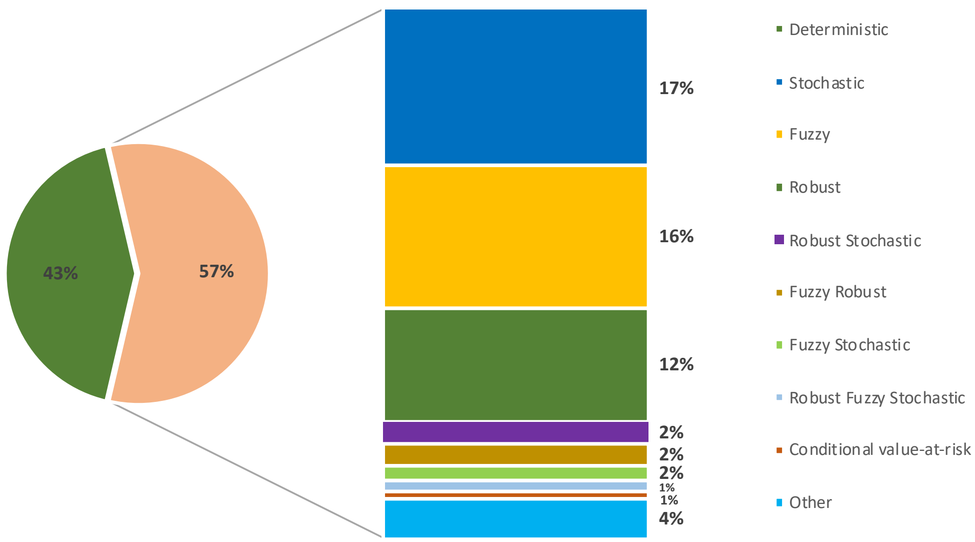

Figure 12. Deterministic and non-deterministic CLSC approaches

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.

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	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.

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

2.5. 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 study, 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 CE at a SC level. Previous literature reviews (See Table 1) revealed that a substantial amount of studies have been conducted in the field of CLSCs so far.

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 study 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 SCs, 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.

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 SCs, 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 research, 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 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. CE rebound occurs when CE 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 SC 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 SCs, 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., absence of child labour throughout the SC; 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 SCs); 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 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 SCs. Of course, the shift from linear to CE has a substantial impact on the design of SCs 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 SCs; 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

SCs. Modelling work aimed at analysing the readiness of existing SCs 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

2.6. Conclusion

The literature review conducted in this chapter has provided valuable insights into the existing research on CLSC design problems. It is evident that considerable research efforts have been dedicated to this area, aiming to address various challenges and improve the efficiency and sustainability of SCs. However, despite the extensive body of literature, certain research gaps and limitations have been identified, which present opportunities for further exploration and improvement in the field.

According to this chapter (whose results have also been published in MahmoumGonbadi et al., 2021), there are some research gaps identified in this field of study which this research tries to address some of the crucial ones; namely, lack of integration of CE principles in SC design problems, the main focus on low treatment strategies (mainly recycling practices) in mathematical models, limited methodological developments and simplistic environmental performance evaluation.

One prominent research gap identified is the limited integration of CE principles in SC design problems. While CLSC aims to create a closed-loop system by incorporating RL and recovering practices, there is a need for a more comprehensive integration of CE principles throughout the design process. This research seeks to address this gap by incorporating CE principles into the mathematical models and methodologies developed for SC design. Current evaluation approaches often rely on simplistic metrics and indicators, which may not fully capture the complex environmental implications of different design decisions. To address this limitation, this research aims to develop more robust approach for evaluating the environmental performance of CSCs.

The limited attention to the downgraded market levels is another key shortcoming in CSC design problems. The existing mathematical models and methodologies often overlook the complexities associated with downgraded market levels. This research aims to bridge this gap by explicitly considering the downgraded market levels in the developed model, capturing their impact on decision-making processes and evaluating their implications on the overall performance of the SC. By addressing this research gap, a more comprehensive understanding of CSC design can be achieved, leading to improved decision-making and enhanced sustainability outcomes.

Another research gap highlighted in the literature is the predominant focus on low treatment strategies, particularly recycling practices, in the mathematical models used for SC design. While recycling plays a crucial role in CLSC, it is essential to consider a broader range of treatment options and strategies, such as remanufacturing, and product reuse. By expanding the scope of treatment strategies in the mathematical models, a more comprehensive analysis of the CLSC design problem can be conducted. This research aims to contribute to the field by considering a wider range of treatment options and evaluating their impact on the overall performance and sustainability of the SC.

CHAPTER 3: PROBLEM STATEMENT AND RESEARCH METHODOLOGY

3.1. Introduction

In this chapter, the proposed network model that forms the foundation of the research is introduced, providing a detailed description of the proposed model, including the underlying assumptions. This is followed by the research methodology of the problem under investigation.

3.2. Problem Statement

Strategic planning involves making important decisions about long-term goals, and it's usually done by top-level managers. The proposed network is formulated as a deterministic model based on the assumption that dependable parameters are available. In this section, the developed bi-objective MILP model is formulated to determine facility locations, optimal product transportation flows and the number of downgraded market levels across the whole CSC.

Designing such a circular network and determining the specific locations to establish different facilities and identifying the number of optimal downgraded 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 CSCs and embedding CE practices in their operations; and to minimise the total number of discarded products, which is vital to improve the overall performance of CSC in terms of sustainability and CE metrics. These objectives can be obtained through making the optimal decisions on facility locations, number of activated downgraded market levels, transportation quantities while considering distinctive recovery options simultaneously, such as reusing, remanufacturing and recycling.

To this end, a multi-product, multi-period and multiple downgraded market level CSC is introduced as shown in Figure 13; forward facilities constitute suppliers, plants, distributors and primary customers and the backward nodes consist of the collection and inspection centres, reusing centres, remanufacturers, recyclers, and disposal centres. In the proposed mathematical CSC model, products that have reached the end of their life will be returned to the collection centres following a certain delay period. The delay refers to the amount of time it takes for the EOL products to be returned to the collection centres after they have reached the superior-level customers. Such delay therefore includes usage time, logistics and transportation time, and any other practical considerations.

The model needs to optimise the CSC based on four main treatment options: reusing, remanufacturing, recycling, and disposing. These options are ranked from the most optimal to the least optimal strategies.

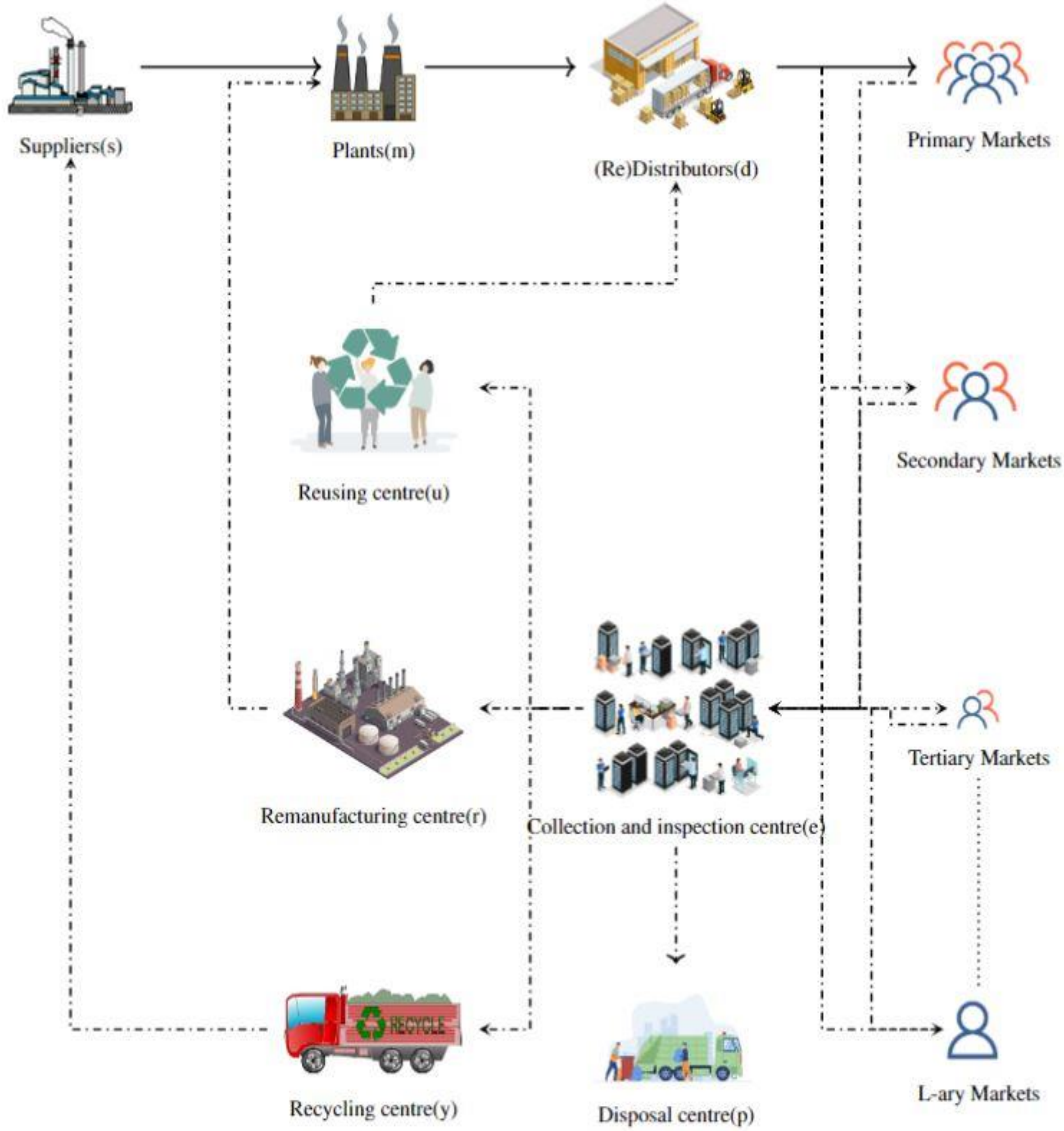

Figure 13. CSC structure and Schematic illustration of product flows in forward and reverse flows

Hence, it shows that CSCs could practically have a number of successive product downgrading by sending more products to be treated in recovering facilities and resulting in activating more downgraded market levels to serve corresponding customer demands.

Three recovering strategies considered for the returned products are described below:

- **Reusing:** the returned goods are of extremely good quality and their life is extended through reusing; products are reutilised as their original function and can be sent directly to distribution centres. They are sold at a discounted price as downgraded products after cleaning.
- **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).
- **Recycling:** Returned products that are not suitable for remanufacturing, are recycled at recycling centres and the materials are reused for displacing of the extraction of virgin raw materials by suppliers.

By 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 usable anymore. Finally, the fraction of returned products which have low quality are sent to the disposal centres for final treatment.

The proposed CSC model incorporates two types of materials as inputs for plants. The first type consists of virgin raw materials sourced from natural resources, only utilised in the primary market levels. The second type comprises non-virgin raw materials, specifically recycled components obtained from EOL products. These non-virgin materials are utilised across all downgraded market levels. As a result, a full displacement has taken into account at the supplier level. In this context, full displacement means completely replacing the use of virgin raw materials with recycled materials in the production process. By achieving full displacement, the reliance on extracting new resources is minimised, and the focus shifts towards reusing and recycling materials, thus promoting sustainability.

The term "downgrading" in CE context, refer specifically to a process where products are sent from superior market levels to recovering centres for reutilisation in inferior market levels. Once the products transported from the collection centres to recovery centres (reusing, remanufacturing, or recycling centres), they are counted as downgraded products.

Downgrading, therefore, aims to extend the lifecycle of products by reintroducing them into lower market levels where their value or functionality may still be relevant. By doing so, it allows the optimisation of resources and reduces waste by giving these products a second life. The process of downgrading contributes to a more sustainable approach by maximising the utility of products and minimising their environmental impact.

As illustrated in Figure 13, various downgraded market levels are introduced in the proposed network based on the number of times the EOL products are returned to the collection/inspection centres.

Reintroduced EOL products (downgraded products) may lead to product cannibalisation in a way that some sales in the superior market levels would be cannibalised by remarketing returned products of almost good quality with reasonable price which causes an internal competition. The cannibalisation effect in a CSC refers to the phenomenon where the introduction of an (*l* - ary) product into the market reduces the demand for the new product, thereby cannibalising its own market share. This effect is often neglected mathematically in the context of CSC models. Hence, the cannibalisation effect is evaluated based on the number of customers who tend to switch from buying primary products to buying an equivalent secondary or other downgraded products with a certain percentage of discount in the original price of the new products. This is a critical aspect in a CSC design as the companies would be reluctant to introduce downgraded products and decline the increased market share and profit due to the risk of cannibalisation among primary and downgraded products sales. This cannibalisation fears procreated the remarkable delays in remarketing and downgrading returned products and even inclination of discarded products. However, according to (Atasu et al., 2008), cannibalisation is less likely to be hurtful for B2C products than B2B commodities. As a consequence, the pricing of the new and downgraded products is a critical factor while designing a CSC mathematical model.

3.3. Research Approach and Philosophical Positioning

In order to achieve the objectives outlined in the problem statement illustrated above, this study aims to develop a mathematical model to solve some of the practical problems that industries are facing once they tend to reorganise their CSCs. Precaution is devoted to developing a comprehensive CSC model that can be practical and useful in 'real world' applications.

As a consequence, models and methods which are employed in this study belong to the Operational Research (OR) discipline. OR involves a wide range of problem-solving techniques and solution methodologies applied in the pursuit of developed decision-making. Consequently, OR research is often undertaken in collaboration between academia and industry. Research in OR concentrates on systematic approach which has close collaboration with social systems to solve problems. Social sciences and OR suggest different ways to utilise the term "Methodology". The social sciences are strong on theory but weak on practice that goes into gaining knowledge. Operational researchers, on the other hand, span theoretical developments underpinning OR methods through to research on practical applications but tend to ignore theory (Jackson, 1993). However, both of them are helping each other to attain more interventions and to learn from them. OR is also acknowledged as a way of utilising mathematical models and development of algorithmic solution approaches rather than expressing management problems and solving them to maintain their performance in an instable environment (Ackoff, 1979).

By considering the philosophical assumptions of management science methods, it becomes evident that the basic modelling mechanism remains consistent. However, there are key distinctions that can be elucidated, as outlined by (Mingers, 2003):

Ontology: This pertains to *what* entities the models seek to represent and assume to exist. In other words, it involves the nature of the elements that the models are constructed from. Different management science methods may focus on different aspects of reality and make varying assumptions about the entities being modelled.

Epistemology: This addresses *how* the models are developed and where they originate from. It concerns the methodology and approach used to construct the models. Various management science methods may employ different techniques, data sources, or theoretical foundations in the process of model creation.

Axiology: This delves into the reasons behind modelling, as well as the values or purposes associated with the models. It explores the motivations driving the use of models in management science. Different methods may be employed with specific objectives in mind, such as prediction, optimisation, decision support, or understanding complex phenomena.

Moreover, the relationship between the science of decision making and the design of systems that support the decision-making process is vital to both academic and practical Operational Research (OR). From a methodological point of view, OR is usually falls within an assumption of positivism, but many researchers acknowledge that theory is restricted by assumptions and context and recognize OR in a perspective known as Design Research since transferring any knowledge generation sense may not be feasible (O'Keefe, 2014). Hence, knowing the principal meta-theoretical assumptions for OR as a discipline is crucial. O'Keefe (2014) classifies OR within ontological, epistemological, axiological, and methodological perspectives. Philosophical assumptions of mathematical modelling as one of the underlying OR methodologies are presented in Table 10, which is adopted from (Mingers, 2003).

Table 10. Framework for characterising the philosophical assumptions underlying OR methodologies and techniques

Methodology	**Synthesis**	**Ontology**	**Epistemology**	**Axiology**
Mathematical Programming	A system to model the relation between several variables using linear or	Relations between the measurable attributes of entities and	Representation by modelling variables, linear and non-linear; constraints,	The purpose is to evaluate various options and decisions

	nonlinear equations and optimise the value of the objective function(s)	processes, together with explicit objective(s)	optimisation software.	thus optimising the objective(s)

Here is a detailed explanation of Table 10 entry for the methodology of Mathematical Programming:

Methodology: Mathematical Programming is a method used to model the relationships between multiple variables using linear or nonlinear equations. It aims to optimise the value of one or more objective functions subject to the given constraints.

Synthesis: Mathematical Programming involves constructing a system that represents the relationships between various variables. These relationships are typically expressed through linear or nonlinear equations. The objective of the modelling process is to optimise the value of one or more objective functions, which may involve maximising or minimising certain variables.

Ontology: In Mathematical Programming, the focus is on modelling the relations between measurable attributes of entities (such as resources, constraints, and decision variables) and processes. These relationships are captured through mathematical equations. The methodology assumes that these entities and their attributes exist and can be quantified.

Epistemology: The modelling process in Mathematical Programming involves representing the entities and their relationships through variables, linear and nonlinear equations, and constraints. These models are constructed using mathematical representations. Optimisation software is often employed to solve the equations and find the optimal values of the objective function(s).

Axiology: The purpose of applying Mathematical Programming is to assess different options and make informed decisions. By optimising the objective function(s) subject to the given constraints, the methodology aids in identifying the best possible solutions. The underlying value lies in achieving the most favourable outcome or maximising the efficiency of a system or process.

In summary, Mathematical Programming is a methodology that constructs models using variables, equations, and constraints to optimise the value of objective function(s). It assumes the existence of measurable attributes, aims to evaluate options, and make optimal decisions based on explicit objectives.

3.4. Research Framework

This research aims to develop a generic CSC model for rationalising multi-echelon, bi-objective CSC under consideration of multiple downgraded market levels by using a mathematical model; specifically, a multi-product, multi-period based model. Figure 14 depicts the outline for this study which comprises the three main phases and each phase contains several related steps which are described thoroughly in the following sub-sections.

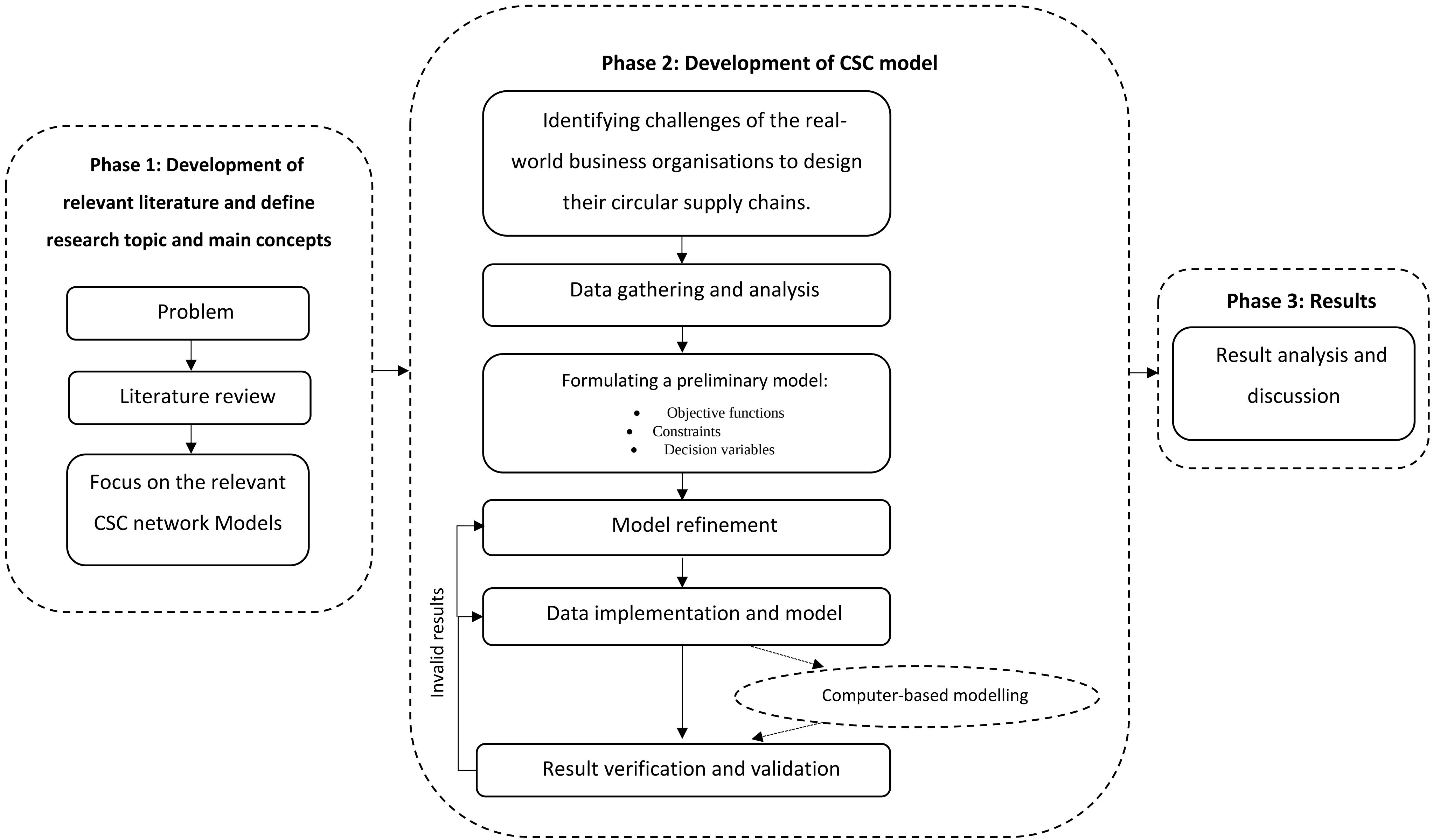

Figure 14. Research framework

3.4.1. Phase 1

Three general steps are introduced in Phase 1: namely problem identification, review of the existing literature and finally, emphasis on the related subject of interest. According to the review of the previous chapter, main focus and concept of this research is coming from the existing gaps in the extent literature.

3.4.2. Phase 2

There are seven steps involved in this phase.

- Understanding and identifying the challenges of the real-world business organisations to design their CSCs: Issues related to applying different recovery options faced by organisation are explored throughout using secondary sources. This information is helpful to ensure the collected data and model the developed model characterize the tackled problem.
- Data gathering and data analysis: The online-based data from similar network design papers is collected such as the number of existing facilities in a region, capacities of the facilities and the anticipated demand in a certain region.
- Objective functions, constraints, decision variables, and input parameters:
    - The objective function is the principal ambition of the formulated model which considers the trade-off among various goals, like maximising the total supply chain profit, minimising the environmental impacts and so on.
    - Potential constraints denote the logical condition of the developed model that must be relaxed by the model. For instance, capacity of facilities allocated to a product or maximum number of facilities can be established in each period.
    - One of the most important components in developing a mathematical model is determining the decision variables. For instance, number of facilities to be established in each period or number of downgraded market levels that will be catered per product per period.

- Input parameters signify the fixed values of collected data. For example, number and location of existing facilities, maximum number of acceptable downgraded market levels in a specific industry sector for each product.

- Model refinement, data implementation and model solving, and result validation and verification: The developed model is solved by using PYTHON programming language and CPLEX solver. The obtained result is evaluated and verified by conducting numerical experiments and a sensitivity analysis. At this stage, the computed results were refined where they were invalid and unreliable.

3.4.3. Phase 3

Finally, the obtained results were examined thoroughly in Phase 3. This phase involves a detailed analysis and interpretation of the results to draw meaningful conclusions and insights. More precisely, in Phase 3, the focus shifts towards a comprehensive examination of the results obtained from the model. This phase involves several key activities:

Analysis of Results: The results generated by solving the formulated model using PYTHON programming language and CPLEX solver are carefully analysed. This analysis involves reviewing the output values, such as the optimal values of decision variables and objective function values.

Interpretation of Results: The meaning and implications of the obtained results are interpreted in the context of the research objectives and the problem at hand. The patterns, trends, and relationships within the data are identified to gain a deeper understanding of the dynamics and outcomes of the CSC design.

Conclusions and Findings: Based on the analysis and interpretation of the results, conclusions and findings are drawn. These conclusions reflect the insights gained from the model and its application to the specific problem under investigation. The key factors influencing the design of CSCs are identified and highlighted the trade-offs and challenges associated with different objective functions and constraints.

Result Validation and Verification: The validity and reliability of the obtained results are further examined through result validation and verification processes by conducting numerical experiments.

Implications and Recommendations: Based on the thorough examination of the results, the implications of the findings for real-world business organizations aiming to design their CSCs are identified. Recommendations are provided to guide decision-makers in implementing the proposed models or strategies.

By conducting a rigorous analysis, interpretation, validation, and verification of the obtained results, Phase 3 aims to provide valuable insights, recommendations, and actionable outcomes for practitioners, policymakers, or further research in the field of CSC design.

3.5. Conclusion

This chapter provided a general description of the problem addressed in this research, dealing with the design of CSCs by introducing the new concept of downgraded market levels. It has also outlined the research approach and philosophical positioning adopted in this study.

Previous studies have not fully incorporated CE principles into their models and frameworks. This research therefore aims to broaden the scope by considering a wider range of treatment strategies, introducing the concept of downgraded market levels and incorporating them into the structure of a mathematical model. The next chapter will illustrate, in a comprehensive way, the elements of such mathematical model.

CHAPTER 4. BI-OBJECTIVE MIXED INTEGER LINEAR PROGRAMMING OF A CIRCULAR SUPPLY CHAIN DESIGN

4.1. Introduction

In this chapter, the focus is on the development of a bi-objective MILP model for designing a CSC. The concept of a CSC involves the integration of CE practices, such as reusing, remanufacturing, and recycling, to promote sustainability and resource efficiency. This chapter presents a comprehensive analysis of the mathematical formulation of the CSC design problem, including model notations, objective functions, constraints, and the adopted solution method.

4.2. Conceptual framework of CSC design problem

This section begins by outlining the conceptual framework of the CSC design problem. It provides a theoretical foundation and highlights the key elements and considerations involved in designing an effective and sustainable CSC. By understanding the conceptual framework, researchers and practitioners can gain insights into the complexity and interdisciplinary nature of the CSC design problem. Therefore, Figure 15 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 number of downgraded market levels to be activated through the network. In practice, CSCs provide an effective means to collect returned goods and perform the relevant treatment strategy, while multiple downgraded market levels 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 substitute for virgin raw materials for as much as possible.
- To determine the product flow among network facilities to maximise the profit and minimise the amount of disposed products.

- To determine the facilities' location(s).

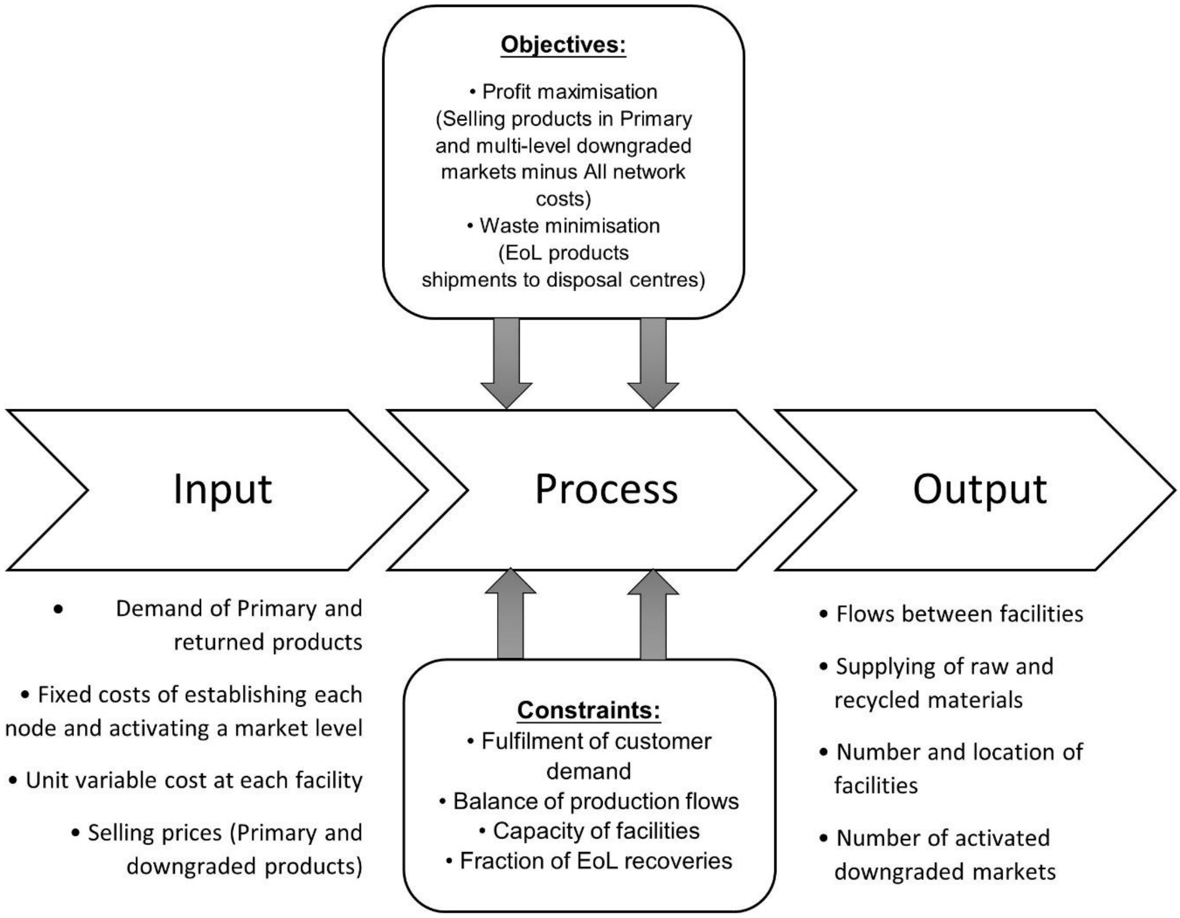

Figure 15. Conceptual framework of CSC mathematical model

4.3. Mathematical formulation

The core of this chapter revolves around the mathematical formulation of the CSC design problem. This section delves into the specific model notations, objective functions, and constraints used in developing the bi-objective MILP model. By formulating the problem mathematically, it becomes possible to quantify the relationships between various decision variables and optimise the system's performance.

4.3.1. Model notations

The model notations are introduced to establish a common language and terminology for the mathematical formulation. This section defines the indices, sets, parameters, and decision variables used throughout the model. It provides clarity and consistency in communicating the problem's mathematical representation. As such, Table 11 presents the notations used in the mathematical formulation of the proposed CSC model.

Table 11. 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 (commodity) types in $P = \{1,2, \dots, k\}$
t	Time period in $T = \{1,2, \dots, t\}$
Sets:	
N_s	Set of supplier nodes
N_m	Set of potential locations for the establishment of manufacturing centre nodes
N_d	Set of potential locations for the establishment of distributor nodes
N_c	Set of customer zones
N_e	Set of potential locations for the establishment of collection and inspection
N_u	Set of potential locations for the establishment of reusing nodes
N_r	Set of potential locations for the establishment of remanufacturer nodes
N_y	Set of potential locations for the establishment of recycler nodes
N_p	Set of potential locations for the establishment of disposal centre nodes
N	Set of all nodes $\{N_s \cup N_m \cup N_d \cup N_c \cup N_e \cup N_u \cup N_r \cup N_y \cup N_p\}$
BN	Set of backward nodes $\{N_c \cup N_e \cup N_u \cup N_r \cup N_y \cup N_p\}$
TN	Set of treatment nodes $\{N_u \cup N_r \cup N_y \cup N_p\}$
RN	Set of treatment nodes $\{N_u \cup N_r \cup N_y\}$
A	Set of all possible network flows, Where:
	$\{A^1 \cup A^2 \cup A^3 \cup A^4 \cup A^5 \cup A^6 \cup A^7 \cup A^8 \cup A^9 \cup A^{10} \cup A^{11}\}$,
	$A^1 = \{(i, j): i \in N_s \wedge j \in N_m\}$
	$A^2 = \{(i, j): i \in N_m \wedge j \in N_d\}$
	$A^3 = \{(i, j): i \in N_d \wedge j \in N_c\}$
	$A^4 = \{(i, j): i \in N_c \wedge j \in N_e\}$
	$A^5 = \{(i, j): i \in N_e \wedge j \in N_u\}$
	$A^6 = \{(i, j): i \in N_e \wedge j \in N_r\}$
	$A^7 = \{(i, j): i \in N_e \wedge j \in N_y\}$
	$A^8 = \{(i, j): i \in N_e \wedge j \in N_p\}$
	$A^9 = \{(i, j): i \in N_u \wedge j \in N_d\}$
	$A^{10} = \{(i, j): i \in N_r \wedge j \in N_m\}$
	$A^{11} = \{(i, j): i \in N_y \wedge j \in N_s\}$

Parameters:	
m	Fixed cost of activating a market level (e.g., administrative and marketing
f_i	Fixed cost of activating nodes
C_i	Capacity associated to node *i*
c_a	Unit variable cost of arc a; note this includes both processing cost at node *i* and transportation cost between node *i* and *j*
ω_i	Supply cost of virgin raw materials at supplier *i*
d_{it}^{lk}	Demand level of customer centre *i* at period *t* for *l*-th market level of product
p_k	Selling price level per unit of product *k*
ψ_{lk}	Discount percentage of price of the primary product *k* at market level *l*
η_{RN}	Recovery rate at recovery centre (Reusing, Remanufacturing, Recycling)
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
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
v_{lk}	1 if *l*-th market level for product *k* is activated; 0 otherwise

4.3.2. Objective functions

The proposed CSC is formulated as a bi-objective MILP model. The first objective function (Eq.1) maximises the total profit by subtracting the total costs of the whole CSC (first component) from the general revenues. Revenue stream includes 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 (p_k). In other words, the recovered units will be sold at a discounted rate (ψ) to customers.

In this study, two types of functions are used to compute the cannibalisation issues; one derived from a discount percentage (ψ_{lk}) of the original price of the new products (p_k). The more we downgrade a returned product, the more discount would be assigned on the price level. The other function assumes partial substituted demand on the lower market levels. To the authors' best knowledge, this study is the first attempt to consider the dynamic interaction between multiple levels of markets in a CE-based supply chain set, and hence capable of well representing the real-world issue.

The primary product is assumed to be sold at a fixed price (p_k) per unit, while the downgraded product is sold at a discounted fraction of the price of the primary products per unit (ψ_{lk}), since they have been produced from returned products. Therefore, the revenue generated by the sale of the primary and downgraded products is denoted by $\psi_{lk} p_k x_{at}^{lk}$. Besides, the total SC costs calculate the operation costs for the activation of a specific market level, the fixed costs of establishing each facility, and unit variable costs.

$$\max obj_1 = \sum_{\substack{a:(i,j)\in A \\ j\in N_c}} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} \psi_{lk} P_k x_{at}^{lk} - \sum_{i\in N} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} \omega_i s_{it}^{lk} - \sum_{l\in L} \sum_{k\in P} m v_{lk} - \sum_{\substack{i\in N \\ i\notin N_c}} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} (f_i/T) y_{it}^{lk} - \sum_{a\in A} \sum_{l\in L} \sum_{k\in P} \sum_{t\in T} c_a . x_{at}^{lk} \quad (1)$$

To adjust the second objective function (Eq.2), the overall time from production to disposal is considered to be aligned with the principles of CE and sustainable SCM. In this objective, the generated waste flow is discounted on the market levels they are collected from. In this way, the model incentivises the activation of further downgraded market levels and promotes the circularity degree of the CSC. Since this function is to be minimised, dividing the amount of disposal by the respective market level will ensure the usage of the disposal centre at inferior market levels after multiple utilisations of the product. This will provide an incentive to the firm to activate further downgraded market levels. By minimising the total amount of products transported to disposal centres, the model is also promoting the waste reduction in order to make CSC as circular as possible as formulated below:

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

4.3.3. Constraints

In terms of constraints, capacity constraint (Eq.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:

$$\sum_{\substack{a:(i,j)\in A \\ i\notin N_c}} x_{at}^{lk} \leq C_i y_{it}^{lk} \qquad \forall\, i,l,k,t \qquad (3)$$

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

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

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

As illustrated in Figure 16, in order for customers to return EOL products to collection centres, there would be a temporal lag denoted by α_i, which results in a delay in the return of EOL products to collection centres throughout the entire time horizon. Additionally, upon exiting collection centres, these products undergo downgrading by a factor of β_i, leading to their downgrading and being sold at downgraded market levels; these two parameters are included in the flow conservation constraint (Eq.4).

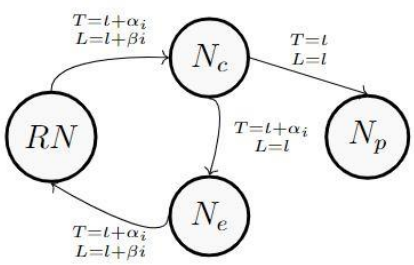

Figure 16. Flow conservation at customer node N_c

In this study, L types of products are considered. The demand for all products is denoted by d_{it}^{lk}, where the total demand for the products is the summation of the demand for the primary products ($l = 1$) and the downgraded products ($l = 2,3, \dots, L$), which is given by $D = \sum_{d\in(1,L)} d_{it}^{lk}$. The demand constraint (Eq.5) is defined for the customer nodes, taking the cannibalisation effect into account, which is the effect of the inferior market level taking sales away from the superior market level. This effect is incorporated by using a summation over the remaining market levels in the constraint being captured by a cannibalisation rate, denoted by γ_t^{lk}, which represents the proportion of demand for the downgraded products that would have gone to the primary product in the absence of the recovered product. Thus, the demand for the new product is reduced by a factor of γ_t^{lk}. Therefore, the effective demand for the primary product is given by $d_{it}^{lk}\left(1 - \sum_{q\in(l+1,|L|)} \gamma_t^{qk}.v_{qk}\right)$. The constraint is formulated in such a way that the total incoming flow of each product for each customer node at each market level in each time period must be less than or equal to the corresponding demand, adjusted for cannibalisation.

$$\sum_{\substack{a:(i,j)\in A \\ j\in N_c}} x_{at}^{lk} \le d_{it}^{lk}(1 - \sum_{q\in(l+1,|L|)} \gamma_t^{qk} v_{qk}) \qquad \forall\, l,k,t \qquad (5)$$

The recovered (reused, remanufactured, and recycled) products are assumed to be produced from returned products at a rate of η_{RN}, which represents the proportion of returned products that are treated in recovering facilities. Thus, the recovered products supply is given by $\eta_{RN}\, x_{at}^{(l-1)k}$, where $x_{at}^{(l-1)k}$ is the quantity of returned products to the collection centres. Constraint (Eq.6) states that a percentage of the returned products from market level *l* can be transported to recovery centres to be treated (reused, remanufactured, or recycled).

$$\sum_{\substack{a:(i,j)\in A, \\ i\in N_e \\ j\epsilon RN}} x_{at}^{lk} \le \eta_{RN}. \sum_{\substack{a:(j,i)\in A \\ j\in N_c \\ i\in N_e}} x_{at}^{(l-1)k} \qquad \forall\; l \in (1+1, L), k, t \in (t+1, T) \qquad (6)$$

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

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

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

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

$$y_{it}^{lk} \le v_{lk} \qquad \forall\, i,l,k,t \tag{9}$$

Constraint (10) denotes that if a node is established at a certain time period, it should always remain open. In other words, it ensures that the decision to open a facility is a permanent one, and once a facility is opened, it cannot be closed in future time periods.

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

Constraint (11) represents the non-negativity and integrality of variables and the ranges each variable can adopt according to their specific features.

$$x_{at}^{lk} \ge 0,\ s_{it}^{lk} \in \mathbb{R} \begin{cases} \ge 0, & i\in N_s,\ l=1 \\ \le 0, & i\in N_p \\ = 0, & otherwise \end{cases},\ y_{it}^{lk} \in \{0,1\}, v_{lk} \in \{0,1\} \tag{11}$$

As can be seen, a very compact and comprehensive mathematical CSC 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 12 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.

Table 12. Number of Parameters, decision variables (DVs) and Equations in comparable CSC 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	**12**	**4**	**11**

4.4. Adopted Solution method

One of the most challenging phenomena in multi-objective problems is the need for identifying the set of Pareto-optimal solutions, thus enabling decision makers to select efficiently the most preferable alternative from a restricted set of non-dominated options.

To this aim, the Augmented Epsilon Constraint Method (AUGMECON) has proven to be among the most efficient solution methods (Mavrotas, 2009), as it produces a set of Pareto optimal solutions for a given set of objective functions by iteratively optimising a single-objective mathematical model.

Whilst tackling the CSC model presented in Section 3, the improved version of the Augmented ε-Constraint Method (Mavrotas & Florios, 2013) was adopted, known as AUGMECON2, as it represents one of the advanced techniques to deal with multi-objective problems for both convex and non-convex functions (Ahmadi & Amin, 2019). In particular, AUGMECON2, while exploring the set of efficient solutions, utilises the concept of bypass jumps, based on the slack/surplus variables values. In this way, it is effective in containing the number of times an optimisation model needs to be iteratively solved.

More in detail, the bypass coefficient shows how many consecutive iterations can be skipped in order to avoid redundant iterations and therefore accelerate the conclusion of the whole algorithm (Mavrotas & Florios, 2013).

The whole procedure associated with this method is described in a pseudo-code format in the following table:

Table 13. Pseudo-code

The pseudo-code of AUGMECON2

1: **Procedure**
2: Create payoff table (lexmax $f_k(x), k = 1, \dots, p$)
3: Set lower bounds lb_k for $k = 2, \dots, p$
4: Compute ranges for objective functions r_k for $k = 2, \dots, p$
5: Define number of grid points g_k for each objective function k
6: Calculate step value for the objective function k: $step_k = \frac{r_k}{g_k}$
7: Initialize counters: $i_k = 0$
8: **For** $k = 2, \dots, p, \quad n_p = 0$ **do**
9:     **While** $i_p < g_p$ **do**
10:         Solve problem P: $\max f_1(x) + eps \times (\frac{S_2}{r_2} + 10^{-1} * \frac{S_3}{r_3} + \cdots + 10^{-(p-2)} * \frac{S_p}{r_p})$
11:         Subject to: $f_k(x) - S_k = e_k \quad k = 2, \dots, p, \quad x \in F$
12:         **If** the Solution is feasible **then**
13:             $n_p = n_p + 1$
14:             Calculate Bypass coefficient $b = int\,(\frac{S_k}{step_k})$
15:             $i_k = i_k + b$
16:         **Else**
17:             $i_p = i_p + 1$
18:         **End if**
19:     **End while**
20: **End for**
21: **Return** Pareto Optimal Set
22: **End procedure**

First, the payoff table needs to be computed (Line 1) to obtain the lower bounds of each objective function (Line 2). As such, according to AUGMECON2, the right hand side of *k*-th objective function (Line 6) 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. In each iteration, the slack/surplus variable which corresponds to the innermost objective function is checked and hence the bypass coefficient is calculated (Line 14). In this way, the exact Pareto optimal front in the bi-objective MILP model is obtained in reasonable computation time.

The application of AUGMECON2 to the CSC model is obtained by defining the optimisation problem *P* as shown below:

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

s.t:

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

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

In Eq.12, f_1 and f_2 correspond to the economic and environmental objectives respectively; s_2 is used as the surplus 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 and eps is a fairly small number between 10^{-6} and 10^{-3} (Mavrotas & Florios, 2013).

The AUGMECON2 method is then coded using the Python programming language and, by adopting the "*docplex*" libraries, mixed-integer programming models are iteratively solved by calling the IBM ILOG CPLEX solver version 12.6. The flowchart of AUGMECON2 adopted from (Mavrotas & Florios, 2013) is illustrated in **Error! Reference source not found.**.

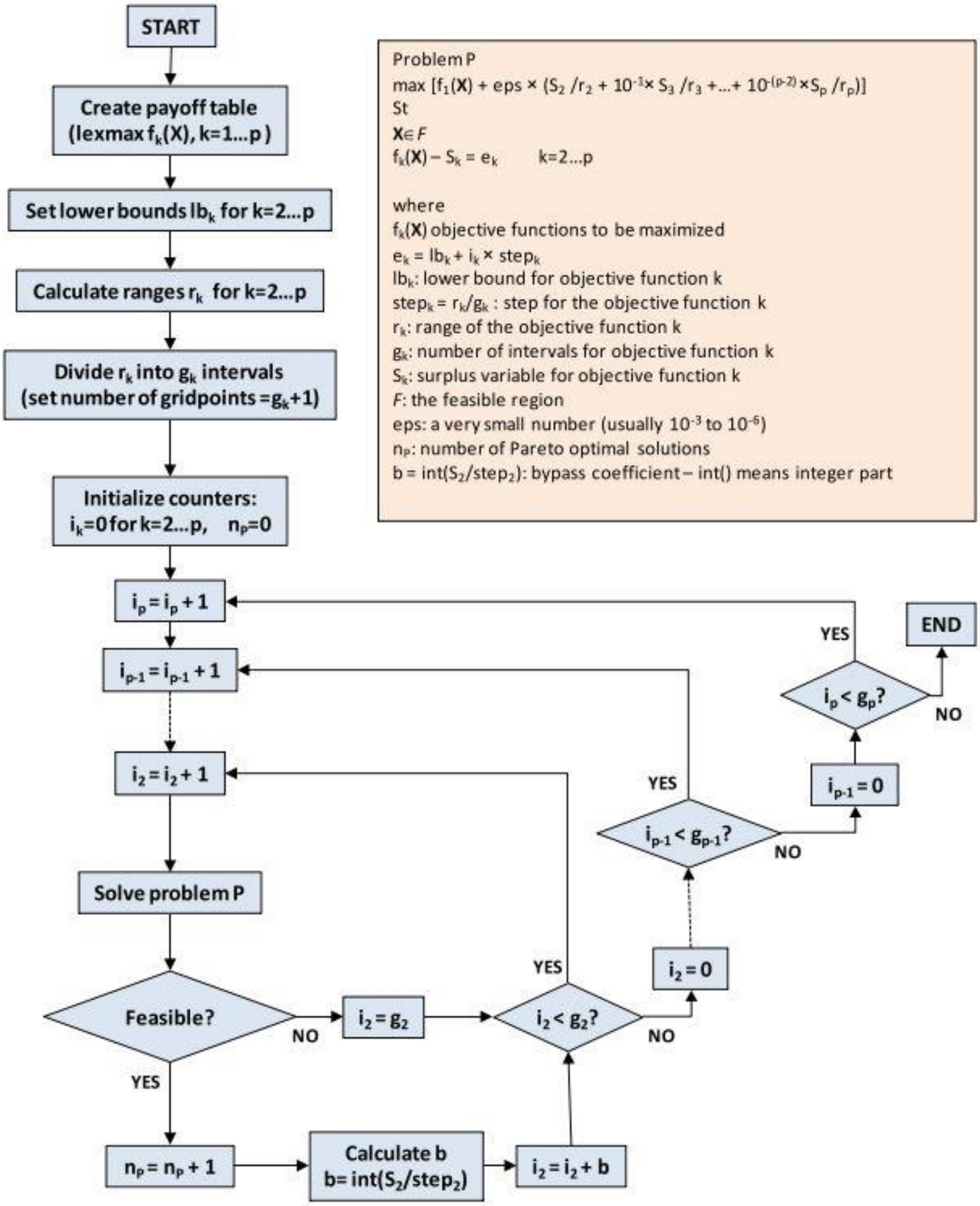

Figure 17. Flowchart of AUGMECON2 method (from Mavrotas & Florios, 2013)

CHAPTER 5: EXPERIMENTAL EVALUATION

In this section, numerical experiments are conducted and described to validate the performance of the proposed mathematical model and verify the solution methodology. All experiments were run on a server equipped with 64bit Intel Xeon CPU at 2.80 gigahertz with 64 gigabytes memory, running Ubuntu 18.04.6 LTS. The details of generated data are described in the following subsections.

5.1. Data generation

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

In order to determine the cardinality of the sets and the values of other parameters, careful scrutiny and review of the literature is conducted in Table 14. Firstly, the number of facilities has a substantial impact on the size of the supply network (Yavari & Geraeli, 2019). Hence, the cardinality of typical facility sets in comparable problems are reviewed; then, ratios among these numbers (see Appendix 1) and appropriate ranges for parameter values are calculated as shown in Table 14 and Table 17. As a result, more realistic values for each set of facilities (**s**: suppliers, **m**: manufacturers, **d**: distributors, **c**: customers, **e**: collection/inspection centres, **u**: reusing centres, **r**: remanufacturers, **y**: recyclers, **p**: disposal centres) and parameters is employed in the computational experiments.

Table 14. 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
(Fakhrzad & Goodarzian,	8	4	2	8	12	-	-	-	-	Test instance
(Shen, 2019)	-	6	-	15	10	-	-	4	-	Test instance
(Tosarkani & Amin, 2019)	5	6	-	15	-	-	2	-	-	Real-world problem

(Ahmadi & Amin, 2019)	5	4	15	44	7	-	5	-	3	Real-world problem
(Masoudipour et al., 2019)	-	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
(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, 2019)	3	2	3	5	3	-	-	-	2	Test instance
(Almaraj & Trafalis, 2019)	5	3	5	10	5	-	-	-	3	Test instance (medium
(Almaraj & Trafalis, 2019)	7	5	7	20	7	-	-	-	5	Test instance
(L. L. Zhen 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

In order to evaluate the performance of the proposed model as well as the solution methodology, three classes of problems with different sizes are defined, as represented in Table 15. In this regard, numerical analyses were also carried out to provide managerial insights into the circular-based supply networks.

Table 15. Problem sizes

Problem levels	**Problem size**	**s**	**m**	**d**	**c**	**e**	**u**	**r**	**y**	**p**	**Total number of facilities**
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
Large Scale	P3	6	3	9	18	9	3	3	6	3	60

The values of some parameters are presented in Table 17. For each parameter, appropriate ranges, based on similar studies available in the literature (Soleimani et al., 2014; Wang et al., 2016), is established. For structuring the computational testbed, instances are generated in a random way, considering uniform distributions for all the parameters, within specified ranges. It is worth noting that, given the presence of markets for reused, remanufactured, and recycled products, a fraction of the demand for primary products might be cannibalised by the existence of the downgraded products.

When the cannibalisation rate is zero (γ_t^{lk}=0), the CSC operates at the superior market level (L=5) where both primary and downgraded products are sold in all sets of Pareto solutions, irrespective of the size of the supply network or the level of customer demand. This is because the introduction of downgraded products does not replace the demand for primary products, and all types of products can coexist in the market without affecting profit or environmental objectives.

On the other hand, when the cannibalisation rate is equal to one (γ_t^{lk}=1), the CSC operates at inferior market levels (L=1) where only primary products are sold, and no downgraded products are available. This is because the introduction of downgraded products does not contribute to the profit objective, and the primary product's demand is fully retained. However, when the environmental objective is also considered, the CSC may activate up to two market levels, and EOL goods are discarded only after two utilisations.

Therefore, the range of the cannibalisation ratio is specified as a uniform fraction $\gamma_t^{lk} \sim U(0, 0.5)$, 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, distribution, collection, recovery, dispose and transportation costs for products manufactured or taken back to the relevant stage in both forward and reverse SCs.

Due to the strategic nature of the model, pre-determined upper bounds for each of the R-options are derived by calculating the average values in the literature as shown in Table 16.

Table 16. Upper bound for recovery options

Paper	Reusing Rate	Remanufacturing Rate	Recycling Rate
(Ramezani et al., 2013)	0.45	0.25	0.15
(Devika et al., 2014)	0.5	0.5	0.5
(M. A. M. A. Kalaitzidou et al.,	0.4	0.3	0.2
(Atabaki et al., 2019)	0.2	0.3	0.3
Average	**0.39**	**0.34**	**0.29**

Table 17. Parameters and their values

Parameters	**Definition**	**Values**
L	Number of market levels	5
P	Number of Products	2
T	Number of Periods	15
f_i	Fixed cost of starting a contract with supplier s	~ U (7,10 million)
	Fixed cost of opening a plant m	~ U (70,150 million)
	Fixed cost of establishing a distribution centre d	~ U (1,2 million)
	Fixed cost of establishing a collection centre e	~ U (0.1,1 million)
	Fixed cost of establishing all recovering centres	~ U (0.1,1 million)
	Fixed cost of establishing a disposal centre p	~ U (0.1,1 million)
m	Fixed cost of activating a market level	~ U (0.1,1 million)
C	Capacity level of supplier s	~ U (18000,42000)
	Capacity level of plant m	~ U (6000,14000)
	Capacity level of distribution centre d	~ U (6000,14000)
	Capacity level of collection centre e	~ U (6000,14000)
	Capacity level of reusing centre u	50% of Distributor capacity
	Capacity level of remanufacturing centre r	50% of Manufacturer capacity
	Capacity level of recycling centre y	50% of Supplier capacity
	Capacity level of disposal centre p	~ U (6000,14000)
c_a	Unit variable cost at forward nodes	~ U (100,1000)
	Unit variable cost at reverse nodes	~ U (10,100)
p_k	Selling price level per unit	~ U (15000,20000)
ψ_{lk}	Discount percentage (% of original price (p_k))	~ U (0,1)
γ_t^{lk}	Cannibalisation ratio (% of ($l-1$) market demand)	~ U (0,0.5)
η_l	Recovery rate	~ U (0,0.5)
α_i	Delay (at customer node)	{0, 1}
β_i	Downgrade (at collection centre)	{0, 1}

5.2. Demand profile scenarios

To tackle the instability in demand, this research proposes three scenarios to consider all potential demand levels that a CSC could possess during a certain time period. From an application perspective, it makes more sense to make the demand profile more stable, by restricting the random element to a small variation ($\pm\rho$) from the initial demand level (D_0). Hence, the computational results of the model for various problem scale (small, medium, and large) under three various demand profiles (Decreasing, Constant, and Increasing) are presented in the following subsections. The effect on each Key Performance Indicator (KPI) is described and the corresponding managerial implications are reported. The demand level of each defined scenario is formulated as follows:

- **Scenario (1) *Decreasing Demand Profile*:**

In scenario (1), which is characterized by a decreasing trend and random fluctuations within $(\pm\rho\%)$, the demand profile is described by equation (14), where D_0 represents the initial demand and $U(-\rho,\rho)$ shows a uniformly distributed random variable between $-\rho$ and ρ.

$$d_{it}^{lk} = D_0.[(1-0.05t)+U(-\rho,\rho)] \qquad \forall\, i \in N_c, t \in T, l \in L, k \in P \tag{14}$$

- **Scenario (2) *Constant Demand Profile*:**

In this scenario, the demand profile (Eq.15) is described as having a constant trend, but with random fluctuations within $\rho\%$ around the initial demand (D_0).

$$d_{it}^{lk} = D_0.[1+U(-\rho,\rho)] \qquad \forall\, i \in N_c, t \in T, l \in L, k \in P \tag{15}$$

- **Scenario (3) *Increasing Demand Profile*:**

Scenario (3) also describes the demand profile as having an increasing trend per time period, along with random fluctuations within $\rho\%$ around the initial demand (D_0).

$$d_{it}^{lk} = D_0.[(1+0.05t)+U(-\rho,\rho)] \qquad \forall\, i \in N_c, t \in T, l \in L, k \in P \tag{16}$$

5.3. Key Performance Indicators (KPIs)

This research is expected to provide a generic formulation to allow various companies to embed CE policies in designing and optimising their SC to comply with regulations. In this regard, some critical Key Performance Indicators (KPIs) are developed for the assessment of

CSC performance based on CE practices. These KPIs are derived by adopting both economic and environmental sustainability perspectives. Moreover, the developed indicators are capable of evaluating the effectiveness and the efficiency of multiple downgraded market levels on the CSC performance from several dimensions (See Table 18).

Table 18. Key Performance Indicators (KPIs)

Number	KPIs	Measurements
1	Number of activated market levels	Active Markets
2	Objective functions	Profitability
		Environmental impact
3	Treatment options	Reused products (%)
		Remanufactured Components (%)
		Recycled materials (%)
		Disposed EOLs (%)
4	Satisfied demand level	Customer demand satisfaction

5.4. Quantifying parameters and their impact

5.4.1. The impact of Cannibalisation on the activated market levels

When the cannibalisation rate is zero ($\gamma_t^{lk} = 0$), the circular CLSC operates at the highest market level (L=5) where both primary and downgraded products are sold in all sets of Pareto solutions, irrespective of the size of the supply network or the level of customer demand. This is because the introduction of downgraded products does not replace the demand for primary products, and all types of products can coexist in the market without affecting the profit or environmental objectives.

On the other hand, when the cannibalisation rate is equal to one ($\gamma_t^{lk} = 1$), the CLSC operates at lower market levels (L=1) where only primary products are sold, and no downgraded products are available. This is because the introduction of downgraded products does not contribute to the profit objective, and the primary product's demand is fully retained. However, when the environmental objective is also considered, the CLSC may activate up to two market levels, and EOL goods are discarded only after two utilisations.

In summary, the impact of cannibalisation on market levels in a CLSC depends on the cannibalisation rate. A zero cannibalisation rate allows for the coexistence of both primary and downgraded products at the highest market level, while a full cannibalisation effect results in the operation of the CLSC at lower market levels with only primary products sold. However, when environmental considerations are taken into account, the CLSC may operate at intermediate market levels and extend the product life cycle through multiple utilisations.

Table 19. Cannibalisation effect

Cannibalisation rate	Problem size	Scenario (1)		Scenario (2)		Scenario (3)	
		min_l	max_l	min_l	max_l	min_l	max_l
$\gamma_t^{lk} = 0$	P1	5	5	5	5	5	5
	P2	5	5	5	5	5	5
	P3	5	5	5	5	5	5
$\gamma_t^{lk} = 1$	P1	1	2	1	2	1	2
	P2	1	2	1	2	1	2
	P3	1	2	1	2	1	2

5.4.2. Displacement Ratio

The environmental impact of implementing CE practices and the reduction of EOL products shipped to disposal centres depends on several factors such as displacement (substitution) rate, which refers to the efficiency of the recycling materials based on the amount of virgin raw materials being displaced for a certain mass of recycled materials.

Recycled products displaces a huge volume of materials from disposals; which is very appealing for companies for their environmental credentials as well as the economic value that would cost them approximately 50% less than purchasing virgin raw materials (Walsh et al., 2015). Hence, displacement rate (DR) is defined as the amount of virgin raw material that can be substituted by a certain mass of recycled materials, which is calculated as follows:

$$DR: \sum_{\substack{a:(i,j)\in A \\ j\in N_m}} x_{at}^{lk} = s_{it}^{lk} + \sum_{\substack{a:(j,i)\in A \\ j\in N_y}} x_{at}^{lk} \tag{17}$$

A higher displacement rate indicates that a larger amount of virgin raw materials can be saved through recycling, which leads to a greater reduction in the environmental impact of the company's operations. Figure 18 illustrates that at the supplier node, the model optimises the supply variable to mitigate the supply of virgin raw materials at downgraded market levels, thereby enhancing the displacement ratio through the substitution of recycled materials. This strategy curbs the rebound effect in a CSC, leading to more sustainable practices. In the proposed model, a full displacement has been considered at downgraded levels as there would be no supply amount of virgin raw materials ($s_{it}^{lk} = 0$) at downgraded market levels.

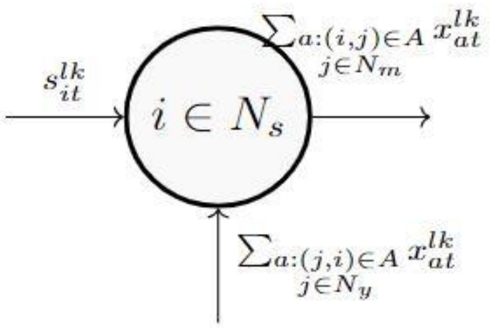

Figure 18. Displacement ratio at supplier

CHAPTER 6: FINDINGS AND IMPLICATIONS

The developed MILP model and the experimental results have produced interesting findings which can contribute to the SCM and CE literature and provide some managerial implications. The findings verify the validation of the proposed model and its applicability to the real world.

In general, results show that introducing downgraded market levels as well as various recovery options presents a significant impact on the whole SC. More specifically, by activating more market levels, the percentage of recollected items from customers increases, and therefore, the circularity degree of the whole CSC improves by keeping the EOL products in the circle for as long as possible. (e.g. P(a.b) in all subsequent figures represents a problem investigated under scenario (a) and size (b) of facilities throughout the network)

6.1. Research Findings

6.1.1. Number of activated market levels

The findings from the analysis highlight the significant influence of various factors on the number of activated market levels in the CSC model. One such factor is the market activation costs, which have a notable impact on the decision-making process. As the costs associated with activating markets increase, firms tend to prioritise maximising profit objectives rather than focusing on environmental considerations. Consequently, fewer market levels are activated, reflecting the trade-off between economic gains and environmental sustainability.

Furthermore, the result reveals the effect of the demand trend on the activation of market levels. When the demand profile shows an increasing trend, indicating a higher demand for downgraded products over the specified time period, it becomes necessary to activate a greater number of downgraded market level to meet customer demands. This is evident in **Error! Reference source not found.**, where the minimum level of activated markets consistently increases as the demand trend shifts from decreasing to constant and increasing (Vertical columns of the matrix in the figure 19). This finding emphasizes the importance of aligning market activation decisions with the evolving demand patterns in order to effectively manage supply and satisfy customer requirements.

Moreover, the analysis indicates that the problem size, i.e., the scale of the instances considered, also plays a role in determining the number of activated market levels. In larger instances with a greater number of facilities across the CSCSN, the set of Pareto solutions exhibits a higher level of activated downgraded market levels compared to the medium and small-sized instances. This outcome suggests that the complexity and scale of the SC influence the optimal configuration of activated downgraded markets.

Taken together, these findings emphasize the multi-faceted nature of market activation decisions in CSC design models. By understanding and managing these factors effectively, companies can make informed decisions that align with their overarching objectives and contribute to the realization of a more sustainable and profitable CSC.

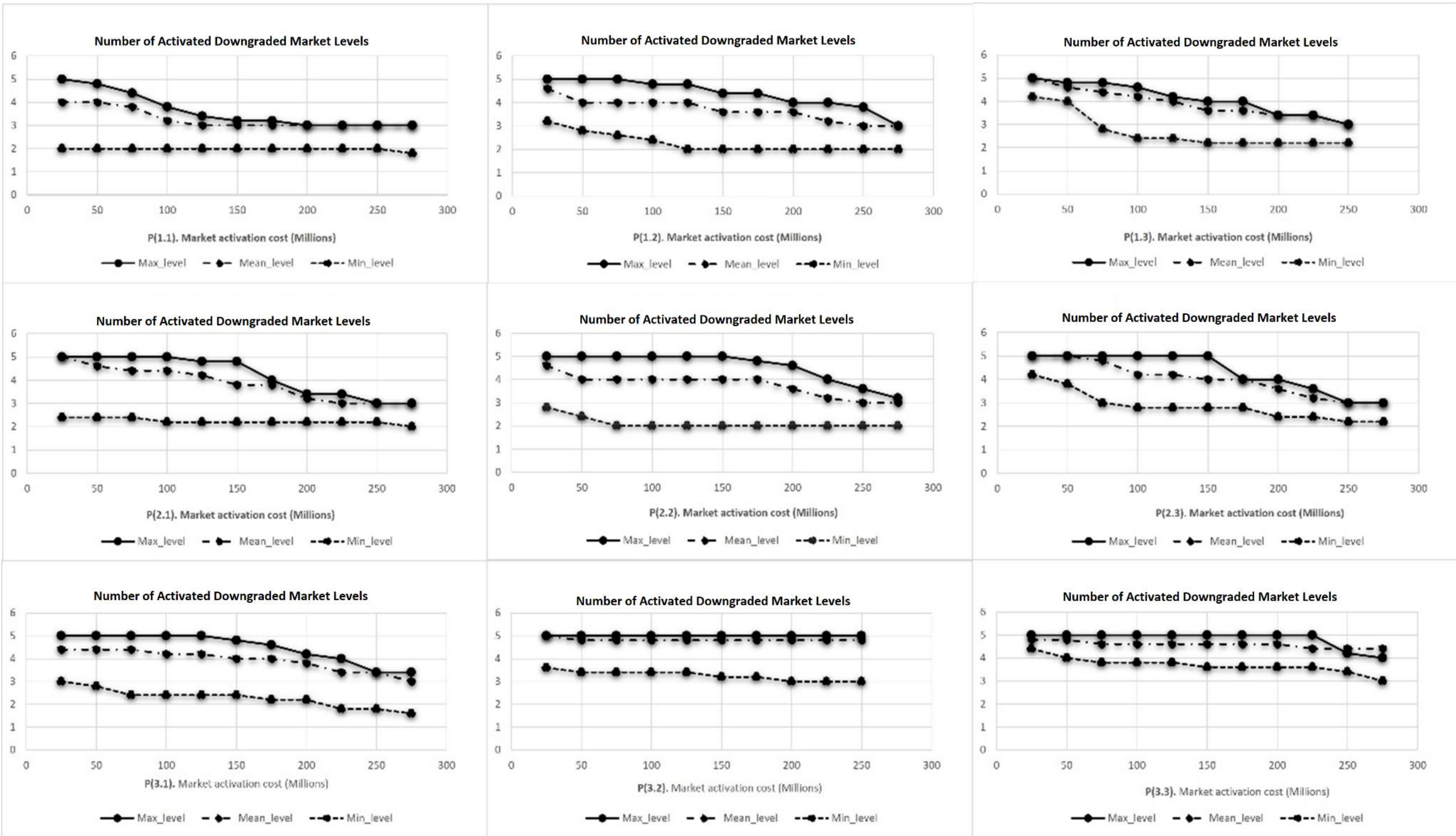

Figure 19. Number of Activated Downgraded Market Levels

6.1.2. Objective functions

The objective functions in the proposed CSC model aim to balance both economic and environmental considerations. Remarketing the returned EOL products will not only generate a new source of revenue but also prevent wasting valuable materials.

The first objective is to maximise the profit of the organizations, which is achieved by considering different market levels and price differentiation. The model seeks to find the optimal combination of market levels that will yield the highest profit.

The second objective is to minimise the total number of discarded products, which is an important environmental consideration. The model achieves this objective by keeping the products in use through remarketing returned EOL products. The results show that activating more market levels is more effective in reducing the number of discarded products. This is because with more market levels, the products have a higher chance of being sold and reused instead of being discarded. In general, manufacturers generate waste if they produce more primary goods, however, in the proposed CSC, fewer products end up in landfills by keeping them in use.

Overall, the proposed CSC model demonstrates that both economic and environmental objectives can be achieved by considering different market levels and price differentiation. Activating downgraded market levels is shown to be more effective in achieving both objectives regardless of the size of companies or the level of customer demands (Figure 20). This is a valuable insight for organizations seeking to optimise their SC operations while also reducing their environmental impact.

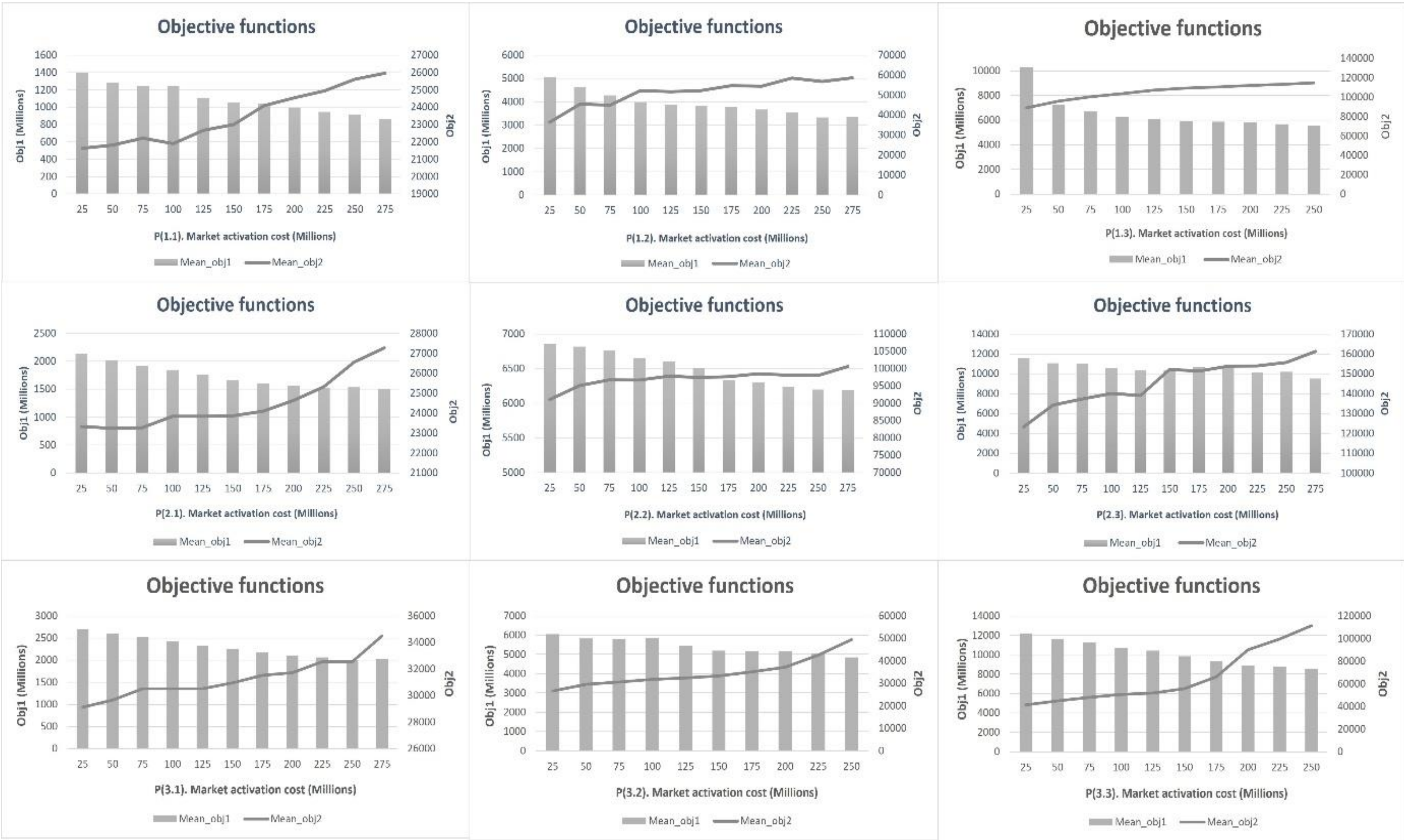

Figure 20. Objective functions

6.1.3. Treatment Option

This KPI focuses on exploring different treatment options for EOL products that have reached the end of their useful life. Instead of simply transporting these products to disposal sites, the proposed model suggests a more sustainable approach by advocating for their recovery. Various recovery options, such as reusing, remanufacturing, and recycling centres, are considered, and the impact of activating different downgraded market levels on the number of discarded products is investigated.

The findings demonstrate that activating a greater number of market levels has a positive effect on reducing the quantity of discarded products and increasing the number of products that are treated in recovery centres. As depicted in Figure 21, as the number of activated market levels increases from L=2 (higher market activation cost) to L=5 (lower market activation cost), the number of discarded products gradually decreases, indicating a shift towards treating them in recovery centres. This shift towards recovery options contributes to the creation of a more CSC, where valuable materials and products are reclaimed and reused instead of being sent to landfills. Among the recovery options considered, reusing a significant percentage of the products emerges as the most feasible and rational choice, followed by remanufacturing and recycling in a cascaded manner. This approach fosters a more sustainable CSC by reducing the volume of products that ultimately end up in disposal sites.

The analysis reveals that by activating more downgraded market levels and promoting recovery options, the CSC can effectively manage and redirect these products towards sustainable treatment facilities, minimising waste and maximising resource utilisation. Overall, the results underscore the significance of activating more downgraded market levels and embracing recovery options in establishing a more profitable and environmentally CSC. By adopting these practices, companies can simultaneously reduce waste, conserve resources, and enhance the overall sustainability of their supply chain operations.

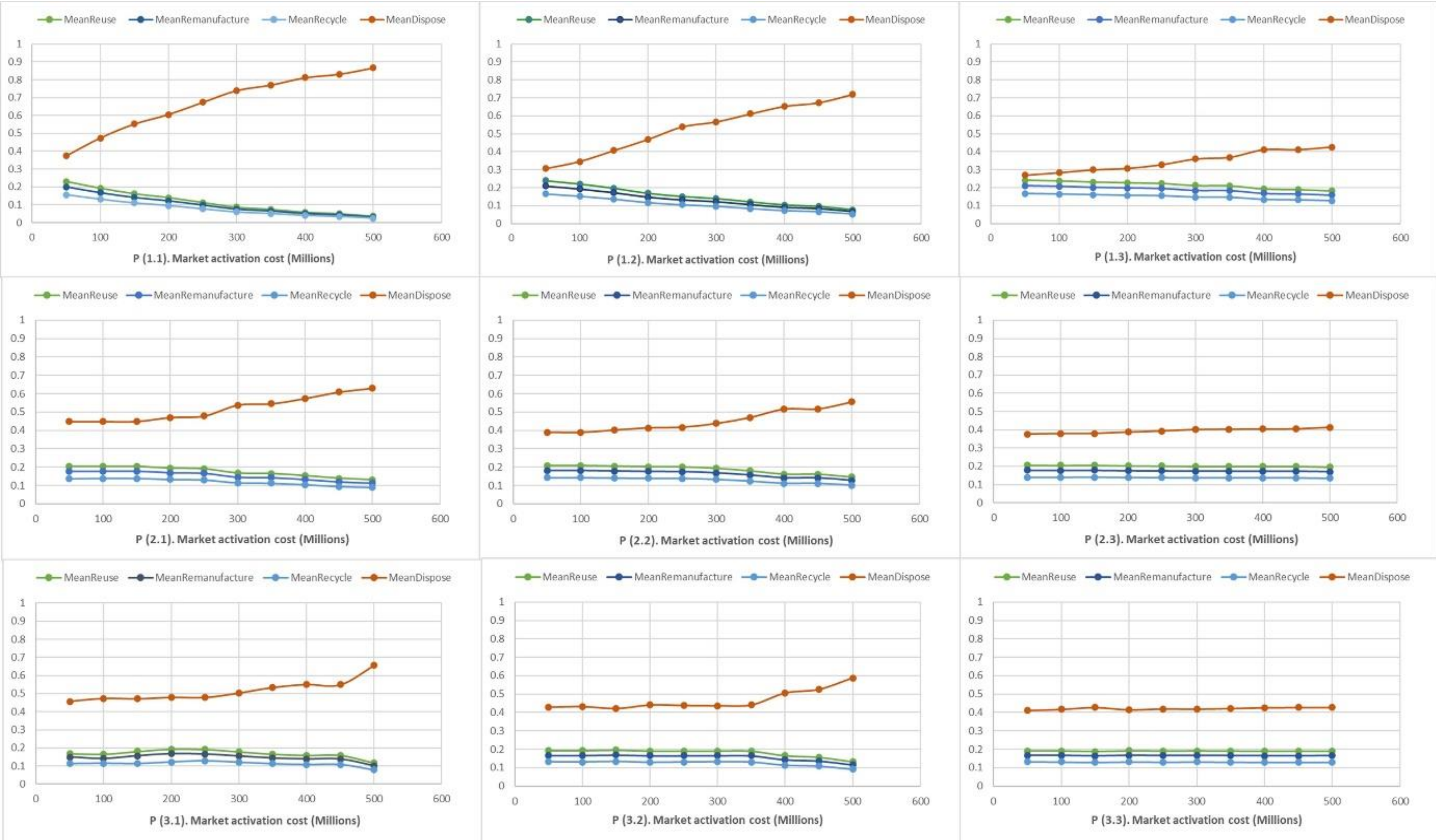

Figure 21. Treatment Options

6.1.4. Satisfied Demand Levels

According to the results, as shown in Figure 22, under the current setting, more demand is satisfied by activating more markets L=5 (Where the market activation cost is lower) in comparison to the traditional SC with only primary or secondary market levels. As mentioned before, the model does not have to meet the demand in total, which is one of the significant features of the model; so, in essence, the model also advises the firm about the optimal market share it needs to target. In this sense, given the overall stability in demand for consumer goods (such as white goods), a less volatile demand profile would be more realistic. The vertical axis in Figure 22 represents the average percentage of the maximum number of satisfied demand in each combination of Pareto-optimal solutions. In this study, the satisfied demand level is based on the market share of each level; in this regard, by activating more market levels at lower market activation costs, the model tries to satisfy more demand from downgraded products, and therefore, more primary resources are saved.

The downgraded products can lead to the cannibalisation of primary market sales. On the contrary, some scholars (Ramani & De Giovanni, 2017) claimed that cannibalisation does not decrease the manufacturers sales, but negatively impacts the company's obtained profit. In order to overcome the negative impact of the cannibalisation of the new products, the recovery costs should be fairly low, or an appropriate price should be assigned to the downgraded products. From a managerial point of view, in order to avoid the severe effect of cannibalisation on a company, a shifting mindset of consumers are required by the governments. Therefore, the businesses could obtain an optimal market share by selling pricey primary products to consumers who prefer buying new products and selling downgraded products to people with environmental consciousness mindset.

According to the authors' best knowledge, CLSC and CE scholars had considered either the absolute substitution (cannibalisation=1) or secondary markets (cannibalisation =0); while in reality, the cannibalisation is somewhere between these two extreme scenarios in the range (0,1). Therefore, a certain degree of cannibalisation might be admissible if downgraded products contribute adequately to profit margin.

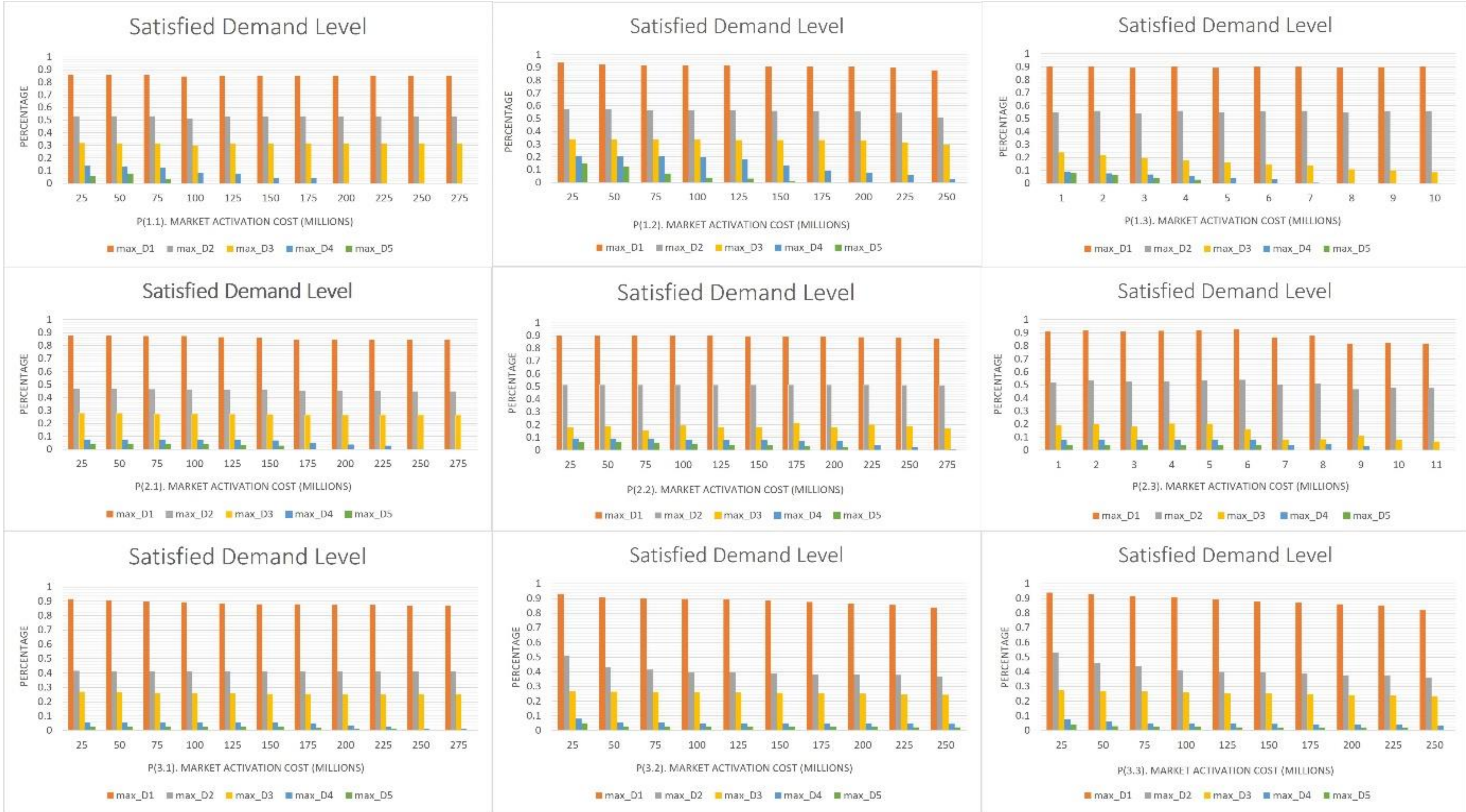

Figure 22. Satisfied demand Levels

6.2. Managerial Insights and Real-World Applications

This study aims to offer practical guidance as well as proper managerial insights to managers and decision-makers in supply chain management. While the model primarily focuses on designing a CSC with multiple downgraded market levels, its principles and findings can be applied across various industries and sectors which some examples are described below.

International White Goods Manufacturing Company: This research highlights the complexity of the problem when applied to an international white goods manufacturing company with a diverse supply chain. The size and scale of their operations matter. In regions with extensive production facilities like Europe and North America, activating a higher number of downgraded market levels can effectively manage their returned products. Instead of sending returned appliances to landfills, they can partner with remanufacturing and recycling facilities to treat the EOL products. This multi-level markets helps increase the number of appliances treated in recovery centres and keep products in use. This proactive approach extends the lifecycle of devices while promoting sustainability.

Fashion Retail Industry: Imagine a fashion retailer operating physical stores and online platforms. Inspired by this research, they can implement the model to significantly reduce clothing waste. The surge in online shopping, driven by the COVID-19 pandemic, has increased the demand for sustainable clothing. The retailer can create a program for collecting and resell gently used or returned garments, keeping these items in circulation. By activating multiple downgraded market levels, including outlets, online platforms, and partnerships for reselling, they can drastically reduce the clothing items that would otherwise end up in landfills. This approach encourages multiple owners for clothing items, ensuring they don't go to waste. Clothes can be resold to a second owner at a lower price if their quality is comparable to brand-new ones. This cycle continues until the clothes are no longer wearable, at which point they can be remanufactured or recycled as a last resort. Individual or business owners can decide how many market levels are practical for their specific situation.

Multinational Consumer Goods: This conglomerate can put the research into practice by activating downgraded market levels and adjusting pricing based on the market segments.

This approach enables them to boost sales for both primary and returned products, ensuring a balance between sustainability and profitability.

These real-world examples demonstrate how businesses can practically apply the managerial insights gleaned from this research. They showcase how factors like market activation costs, demand trends, and the scale of operations can be leveraged to make informed decisions about activating downgraded market levels that align with sustainability and profitability objectives within CSC.

CHAPTER 7: DISCUSSION AND CONCLUSIONS

7.1. Summary of Chapters

This thesis is organized into several chapters, each focusing on a specific aspect of the research and contributing to the understanding and resolution of the problem at hand. The chapters are structured in a logical progression to provide a comprehensive analysis and develop solutions to the research problem.

Chapter 1 provided an overview of the research conducted in this thesis. It introduced the research aims and objectives, along with a general overview of the developed model, highlighting its main features and fundamental principles.

Chapter 2 offered a systematic literature review (SLR) conducted on closed-loop supply chains (CLSC) and reverse logistics. The chapter discussed the research methodology employed for the SLR, including source identification, selection, evaluation, and data analysis. It also highlighted the research agenda for CLSC research, emphasizing the contribution made by this thesis.

Chapter 3 delved into the research methodology employed in this study. It provided an introduction to the chapter, giving an overview of its contents. The problem description is presented in detail, highlighting the specific challenges and issues addressed in the research. The chapter then discussed the research approach and philosophical review, explaining the chosen approach and the underlying philosophical considerations. Additionally, the chapter presented the research framework, outlining the different phases involved in the study.

Chapter 4 explained the bi-objective mathematical CSC model, along with the objective functions, constraints, and the adopted solution method, providing a thorough explanation of the generic optimisation model.

Chapter 5 presents the experimental evaluation conducted as part of this research. The chapter discussed the findings and implications derived from the experiments, shedding light on the key performance indicators, activated market levels, and objective functions.

The final two chapters engaged in a detailed findings and discussion of the research, analysing and interpreting the findings in light of the research objectives. The last chapter mainly outlined the contributions of the research, encompassing contributions to the area of study, model development, and practical implications. Eventually it concluded with a discussion of the limitations of the research and suggestions for future research directions.

7.2. Discussion

The adoption of CE principles into SCs has been gaining momentum in the past decade. In this regard, the literature review section of this study tries to understand whether the current SC modelling approaches can support the transition toward a CE. The main findings of reviewing the academic literature highlighted that there is a disconnection between SC design models and the founding principles of a CE; particularly relying on reductionist sustainability measurement methods and failing to address CE implementation.

While the academic literature has developed an abundant stream of work related to the mathematical models for SC design problems, such modelling proposals tend to be over-specific and lack generality.

In order to fill this gap, this research proposes a comprehensive approach considering various recovery options - such as reusing, remanufacturing, and recycling - as a decision-making support to define the optimal number of downgraded market levels in CSC. The proposed tool is based on a bi-objective optimisation MILP model that integrates CE principles into SC mathematical models, by maximising profit and minimising environmental impact. The AUGMECON2 algorithm is utilised to compute Pareto-optimal solutions for the proposed bi-objective model on a synthetic dataset, EOL built upon realistic assumptions stemming from an analysis of the related literature. The results show that activating a higher number of downgraded market levels and implementing various recovery options simultaneously can significantly reduce the number of discarded products and create a more circular supply chain.

In this context, multiple downgraded market levels have emerged as an effective strategy to achieve both environmental and economic benefits. Specifically, activating a higher number of downgraded market levels (beyond just secondary markets) in a CSC not only contributes to reducing waste but also provides businesses with additional revenue streams.

From an environmental perspective, activating downgraded market levels enables the utilisation of products at their fullest capacity. When a product reaches its end of life, it can be reused, disassembled, and remanufactured or recycled to extend its useful life, creating a circular system. The products can then be sold to different downgraded markets, from high-end to low-end, depending on their conditions. By doing so, the CSC can reduce waste generation and decrease environmental pollution, which ultimately helps businesses comply with government regulations.

Moreover, having a higher number of active downgraded market levels also offers significant economic advantages. By maximising the use of the products, businesses can generate additional revenue streams, reduce their production costs, and enhance their brand reputation. The utilisation of the products at different market levels allows businesses to target different consumer groups, which expands their customer base and increases their sales volume. This approach also creates opportunities for innovation and differentiation, as companies can design products that can be easily disassembled and reused.

Furthermore, activating a bigger number of downgraded market levels aligns with government regulations and promotes a CE. The EU Waste Framework Directive requires the adoption of waste prevention strategies and aims to reduce waste generation by 50% by 2030. Incorporating downgraded market levels in a CSC aligns with the principles of CE and encourages businesses to adopt sustainable practices. Thus, companies that adopt this approach can not only comply with government regulations but also create a competitive advantage for themselves by reducing costs and generating revenue streams. Therefore, the adoption of a CSC with multiple downgraded market levels is a win-win strategy for businesses, the environment, and society as a whole. Speaking of government regulations and policies, it is noteworthy that policies aimed at increasing the cost of landfill and promoting recycling can have a significant impact on the decision to establish facilities in a CSC based on CE principles. For instance, landfill taxes can increase the cost of EOL product disposal, making it more expensive to dispose of waste in landfills, and thus incentivising firms to invest in other recovering facilities. Similarly, recycling taxes can increase the cost of recycling and incentivise firms to invest in more efficient and cost-effective recycling technologies, which can lead to a reduction in overall costs and increased revenue streams. Overall, policy options such as landfill taxes and recycling taxes can help to promote the adoption of CSCs and can encourage firms to pursue more sustainable and environmentally friendly business practices. The results also show that market activation costs are important consideration while designing CSCs. Market activation costs refer to the costs of introducing a new or downgraded product or service to the market.

Moreover, the model experiments suggest that a certain degree of cannibalisation can be accepted at any market level, as long as downgraded products contribute adequately to profit margins, thus counterbalancing the effect of upper-level cannibalisation.

The optimal market share for a manufacturer can be obtained by selling primary products to consumers who prefer new products and downgraded products to consumers with an environmental consciousness mindset.

Overall, this research provides valuable insights into the decision-making process while designing all tiers of CSCs and highlights the importance of considering recovery options, downgraded market levels activation, and consumer preferences to achieve more sustainable and profitable business operations.

7.3. Contributions of the Research

The research identifies and addresses significant gaps in the field of Closed-Loop Supply Chain (CLSC) research, particularly in the context of Circular Economy (CE) principles. It makes significant contributions to the area of study related to SCM, developing a mathematical model and to the implementation of CE principles in real-world case scenarios.

7.3.1. Contributions to the Area of Study:

- The study addresses the research gap related to the limited integration of CE principles in Supply Chain (SC) design problems. It contributes by incorporating CE principles throughout the SC design process. This integration aims to create more sustainable and closed-loop systems, aligning SCs with the principles of CE.

- The research offers a more robust approach for evaluating the environmental performance of CLSC. It recognizes the limitations of simplistic metrics and indicators commonly used in existing models and methodologies. By providing a comprehensive evaluation framework, the study enhances our understanding of the complex environmental implications of different design decisions.
- The thesis highlights the need for more comprehensive and generalized modelling proposals that integrate recovery options and consider environmental impact. By proposing a generic approach, it provides a novel perspective on SC design based on CE principles.
- It highlights the need for a better empirical grounding and knowledge transfer in CLSC research, emphasizing the importance of real-world case studies and empirical validation to enhance the practical relevance of the field, especially in the context of emerging economies.
- It recognizes the disjointed nature of decision-making in CLSC research, calling for the development of novel approaches that incorporate all three decision levels (strategic, tactical, and operational) for better integration.
- The research expands the scope of treatment options and strategies considered in CLSC design. While recycling is essential, the study recognizes the need to include a wider range of treatment strategies such as remanufacturing and product reuse. By doing so, the research provides a more comprehensive analysis of the CLSC design problem, offering insights into the implications of different treatment strategies on overall SC performance and sustainability.
- It acknowledges the reductionist view of CE in existing literature and advocates for the development of design configurations fully inspired by CE principles, with an emphasis on reducing production and consumption.
- The research identifies a lack of consideration for social dimensions in CLSC design models and emphasizes the need for better integration with Social Life-Cycle Analysis approaches.
- It recognizes the inherently multi-objective nature of CLSC design problems, emphasizing the importance of developing multi-objective models that incorporate criteria from economic, environmental, and social perspectives.
- The research acknowledges the limitations of current methods for assessing sustainability dimensions and calls for the development of novel assessment methods and approaches.

7.3.2. Contributions to Model Development:

- The study acknowledges the need for methodological developments to address the inherent complexities of CLSC design problems. It contributes by developing multi-objective mathematical models and solution methods that can accurately address the multi-faceted nature of sustainability issues in SC design.

- The research proposes a bi-objective Mixed-Integer Linear Programming (MILP) model that integrates CE principles into SC mathematical models, aiming to maximize profit and minimize CE-based environmental impact.
- The study addresses the research gap concerning the often overlooked complexities associated with downgraded market levels in CLSC design problems. By explicitly considering these levels in the mathematical models, the research captures their impact on decision-making processes and evaluates their implications for the overall performance of the SC.
- It introduces the AUGMECON2 algorithm for computing Pareto-optimal solutions and demonstrates its effectiveness in obtaining optimal results for the proposed bi-objective model.
- The research provides practical insights and actionable solutions for SC design by considering various recovery options, including reusing, remanufacturing, and recycling, and explicitly incorporating downgraded market levels.

7.3.3. Contributions to Practice:

- The research has practical implications for businesses and practitioners seeking to adopt sustainable and profitable supply chain operations.
- The research emphasizes the importance of integrating CLSC design literature with recent legislative initiatives related to CE, such as Extended Producer Responsibility and Right-to-Repair schemes. It calls for modelling work to assess the readiness of existing SCs to adapt to new legislation, thus bridging the gap between research and policy implementation.
- It emphasizes the importance of considering government regulations and policies, such as landfill taxes and recycling taxes, in SC design decisions to gain a competitive advantage and contribute to a more sustainable business environment.
- By activating a higher number of downgraded market levels and implementing various recovery options, companies can significantly reduce waste generation, environmental pollution, and disposal costs, while generating additional revenue streams and enhancing brand reputation.

Overall, the research provides a comprehensive roadmap for addressing the identified research gaps and limitations in the field of CLSC research and contributes to advancing the integration of CE principles in supply chain modelling and decision-making.

7.4. Limitations and future research

Future directions of research in this area could focus on several key aspects to further advance the understanding and applicability of the proposed model:

- Real-world Applications: One direction for future research is to extend the dataset and validate the proposed model using real-world data from specific industries, such as the white goods sector or other relevant sectors. This would involve collecting and analysing data from actual supply chains, considering factors like product characteristics, market dynamics, and recovery options specific to those industries. By applying the model to real-world scenarios, researchers can evaluate its effectiveness, identify potential challenges, and fine-tune the model parameters and constraints for practical implementation.
- Social Sustainability Considerations: While the proposed model focuses on maximising profit and minimising CE-based environmental impact as objective functions, future studies could incorporate additional dimensions of sustainability, specifically addressing social sustainability and impact. This would involve integrating social metrics and indicators into the decision-making process, considering aspects such as worker well-being, community engagement, and ethical considerations. By expanding the objective functions to include social sustainability, the model would provide a more holistic approach to evaluating the overall sustainability performance of closed-loop supply chains.
- Uncertainty and Scenario-Based Optimisation: Another avenue for future research is to explore the role of uncertainty and incorporate scenario-based optimisation techniques into the model. In real-world supply chain operations, uncertainties related to demand fluctuations, market conditions, and resource availability are common. By considering uncertainty explicitly in the model, researchers can develop robust decision-making approaches that account for different potential scenarios and their associated risks. This would enhance the model's suitability for real-world management purposes, enabling supply chain managers to make informed decisions under varying conditions and uncertainties.
- Integration of Technological Innovations: The research could also explore the integration of emerging technologies and innovations into the proposed model. For example, advancements in data analytics, Internet of Things (IoT), and blockchain can enable more accurate tracking and traceability of products throughout the CSC. Incorporating these

technologies into the model would provide opportunities for enhanced transparency, efficiency, and collaboration among supply chain partners. Future research could investigate how these technological advancements can be integrated into the model to further optimise CSC operations and support the implementation of CE principles.

By addressing these future research directions, scholars can advance the understanding and practical applicability of SC design models for CE implementation. These advancements will contribute to more sustainable and profitable SC operations across various industries, paving the way for a more circular and environmentally conscious business environment.

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APPENDICES

APPENDIX 1: DETAILED INFORMATION FOR LITERATURE REVIEW

This appendix collects some tables derived from the literature analysis presented in Chapter 2, 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
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 Optimisation	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
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 Optimisation in Industrial Engineering	1

APPENDIX 2: PYTHON CODE

A. MAIN MODEL (BI-OBJECTIVE MODEL)

```
import numpy as np                    # A library for the mathematical functions
import docplex.mp.model as cpx        # CPLEX solver
from random import random             # Generate a random number
import statistics                     # Declaring a simple data-set consisting of real valued positive integers
import math                           # Extends the list of mathematical functions
import sys                            # Provides various functions and variables that are used to manipulate
                                        different parts of the Python runtime environment
from time import process_time         # Returns the float value of time in seconds of the sum of the system
                                        and user CPU time of the current process


TIMELIMIT = 36000

# Importing the instance as module
my_module = sys.argv[1]
exec( 'from %s import* ' %my_module.rsplit('.', 1)[0])

GRIDPOINTS = int(sys.argv[2])

mar=int(sys.argv[3])

# Get ready for output
results = []
results.append(my_module)


time_start = process_time()


s=Supplier               # Suppliers
m=s+Manufacturer         # Manufacturers
d=m+Distributor          # Distributers
c=d+Customer             # Customer centres
e=c+Collector            # Collection and inspection centres
u=e+Upgrader             # Reusing centres
r=u+Remanufacturer       # Remanufacturing centres
y=r+Recycler             # Recycling centres
w=y+Disposal             # Disposal centres

"""Sets"""
N_s =[i for i in range(1,s+1)]        # Set of suppliers
```

```
N_m =[i for i in range(s+1,m+1)]    # Set of Manufacturers
N_d =[i for i in range(m+1,d+1)]    # Set of Distributers
N_c =[i for i in range(d+1,c+1)]    # Set of Customer centres
N_e =[i for i in range(c+1,e+1)]    # Set of Collection and inspection centres
N_u =[i for i in range(e+1,u+1)]    # Set of Reusing centres
N_r =[i for i in range(u+1,r+1)]    # Set of Remanufacturing centres
N_y =[i for i in range(r+1,y+1)]    # Set of Recycling centres
N_p =[i for i in range(y+1,w+1)]    # Set of Disposal centres

# Nodes
N= N_s + N_m + N_d + N_c + N_e + N_u + N_r+ N_y + N_p   # All nodes
BN= N_e + N_u + N_r + N_y + N_p                # Backward Nodes (Used in Backward Constraints)
IN= N_u + N_r + N_y + N_p                      # Treatment Nodes


#Arcs
A1=[(i,j) for i in N_s for j in N_m]    # Arc from Supplier to Manufacturing centre
A2=[(i,j) for i in N_m for j in N_d]    # Arc from Manufacturing centre to Distribution centre
A3=[(i,j) for i in N_d for j in N_c]    # Arc from Distribution centre to Customer centre
A4=[(i,j) for i in N_c for j in N_e]    # Arc from Customer centre to Collection/inspection centre
A5=[(i,j) for i in N_e for j in IN]     # Arc from Collection/inspection centre to All the Treatment centres
A6=[(i,j) for i in N_y for j in N_s]    # Arc from Recycling centre to supplier
A7=[(i,j) for i in N_r for j in N_m]    # Arc from Remanufacturing centre to Manufacturing plants
A8=[(i,j) for i in N_u for j in N_d]    # Arc from Reusing centre to Distribution centre
A=A1+A2+A3+A4+A5+A6+A7+A8               # All arcs through the network


"""Parameters"""
# Demand-related parameters
Demand = {(i,l,k,t): Dd[j-1][l-1][k-1][t-1] for i in range(d+1,c+1) for j in range(1,Customer+1) for l in range(1,L+1) for k in range(1,P+1) for t in range(1,T+1)}    # Demand
CE= {(l,k,t): cae[l-1] for l in range(1,L+1) for k in range(1,P+1) for t in range(1,T+1)}   # Cannibalisation effect based on market, product and period (Used in Demand constraint)


# Price-related parameters
Price = {k:Prod_Price[k-1] for k in range(1,P+1)}                 # Price levels
Disc = {(l,k): iii[l-1]  for l in range(1,L+1) for k in range(1,P+1)}     # Final deducted price level at market l (Used in Revenue expression of objective function)

# Delay function
delay_n= []          # Create a list for delay time at node i (There would be a certain delay at customer node)
def delay(Nodes):
  for dl in Nodes:          # for each node
    if dl in range(d+1,c+1):    # if node is the Customer centre
      delay_n.append(Dly[1])  # add 1 to the Delay list
    else:               # Otherwise
      delay_n.append(Dly[0])  # add 0 to the list
```

```
delay(N)

#Downgrade function
downgrade_n=[]                    # Create a list for downgrading at node i (EOL products will be downgraded
as soon as they reach to the collection centre)
def downgrade(Nodes):
   for dw in Nodes:              # for each node
      if dw in range(c+1,e+1):     # if node is Collection centre
         downgrade_n.append(Dwngrd[1])    # add 1 to the Downgrade list
      else:                     # Otherwise
         downgrade_n.append(Dwngrd[0])    # add 0 to the list
downgrade(N)

# Unit variable cost of all arcs (Transportation, Operation,...)
U_cost={(i,j): unit_cost[i-1] for (i,j) in A}


Flag=np.zeros([GRIDPOINTS+1],dtype=int)

# Model
mdl = cpx.Model(name="CLSCAug")


output_file_kpi_batch = "kpi_batch.txt"


verbose_file_kpi_batch = "verbose_results"


#============================================================
"""Decision Variables"""
# create flow variables for each couple of nodes
# x(a,l,k,t) is the flow going out of node i to node j for each market level l for each product k at time period
t
x=mdl.continuous_var_dict(((a,l,k,t) for a in A for l in range(1,L+1) for k in range(1,P+1)for t in
range(1,T+1)),name='x')
# binary variables to establish facilities
y=mdl.binary_var_dict(((i,l,k,t) for i in N for l in range(1,L+1) for k in range(1,P+1)for t in
range(1,T+1)),name='y')
# binary variables for activating a downgraded market level
v=mdl.binary_var_dict(((l,k) for l in range(1,L+1) for k in range(1,P+1)), name='v')
# integer variables for supplying raw materials
supply=mdl.continuous_var_dict(((i,l,k,t)for i in N for l in range(1,L+1) for k in range(1,P+1)for t in
range(1,T+1)),name='supply',lb=-1000000)
# Auxiliary variables
slack=mdl.continuous_var(name="epsilon_slack")
#============================================================

"""Objective function"""
```

```
#obj1:
# Revenue = Discount level * Product Price * Transportation flow
Revenue=mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in range(1,L+1) for k in range(1,P+1)for t in range(1,T+1))

# each arc comes with a cost. Minimise all costed flows
# Cost = (Supply cost +market activation cost + fixed facility establishment cost + Unit variable costs at each entity)
Cost=mdl.sum(SupplyCost[i-1]*supply[i,l,k,t] for i in N for l in range(1,L+1) for k in range(1,P+1)for t in range(1,T+1))+mdl.sum(mar*v[l,k] for l in range(1,L+1) for k in range(1,P+1))+mdl.sum((FC[i-1]/T)*y[i,l,k,t] for i in N if i not in N_c for l in range(1,L+1) for k in range(1,P+1)for t in range(1,T+1)) +mdl.sum(U_cost[a]*x[a,l,k,t] for a in A for l in range(1,L+1) for k in range(1,P+1)for t in range(1,T+1))

Profit = mdl.sum(Revenue-Cost)

#obj2:
Disposal=mdl.sum(x[a,l,k,t]/l for a in A if a[1] in N_p for l in range(1,L+1) for k in range(1,P+1)for t in range(1,T))

Disposal_slack = Disposal + slack

mdl.print_information()

#==============================================================

# Constraints:

# for each node, total outgoing flow must be smaller than available quantity
# 1. Capacity COnstraints
for i in N: # for all nodes
   if i not in N_c:
      for l in range(1,L+1): # for all market levels
         for k in range(1,P+1): # for all products
            for t in range(1,T+1): # for all periods
                              mdl.add_constraint(mdl.sum(x[a,l,k,t] for a in A if a[0]==i)<=Cpy[i-1]*y[i,l,k,t],ctname='capacity')
                # the total amount of shipped products in arc a should be less than the capacity of node i (the origin).


# 2. Balance constraints
for i in N: # for all nodes
   for l in range(1,L+1):
      for k in range(1,P+1): # for all products
         for t in range(1,T+1): # for all periods
            mdl.add_constraint(mdl.sum(x[a,l+downgrade_n[i-1],k,t+delay_n[i-1]] for a in A if a[0]==i if a[1] not in N_p  if l+downgrade_n[i-1]<=L if t+delay_n[i-1]<=T) # for all market levels) # Exiting flows from all nodes apart from disposal centres
```

+mdl.sum(x[a,l,k,t+delay_n[i-1]] for a in A if a[0]==i if a[1] in N_p if t+delay_n[i-1]<=T) # Exiting flow from disposal centre
-mdl.sum(x[a,l,k,t]for a in A if a[1]==i if a[1] not in N_e) # Entering flow to all nodes apart from Collection/inspection centre
-mdl.sum(x[a,l,k,t+delay_n[i-1]]for a in A if a[1]==i if a[1] in N_e if t+delay_n[i-1]<=T)==supply[i,l,k,t] ,ctname='Balance') # Entering flow to Collection/inspection centre

```
# for each customer node, total ingoing flow must be smaller than demand
# 3. Demand Constraints:
for i in N_c:
    for l in range(1,L+1): # for all market levels
        for k in range(1,P+1): # for all products
            for t in range(1,T+1): # for all periods
                mdl.add_constraint(mdl.sum(x[a,l,k,t] for a in A if a[1]==i ) <= Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for q in range(l+1,L+1))),ctname='Demand')
            # Transported products should be less than or equal to total demand considering cannibalisation effectt at each market level.


# 4. Recovering constraint (Max Reusing)
for l in range(1,L): # for each market level
    for k in range(1,P+1): # for each product
        for t in range(2,T): # for each time period
                mdl.add_constraint(mdl.sum(x[a,l+1,k,t] for a in A5 if a[1] in N_u )<= Recovery_max[0]*mdl.sum(x[b,l,k,t] for b in A4), ctname='Recovery1')
            # Transported products to collection/inspection centres should be more than a fraction of products transported to Reusing centres

# 5. Recovering constraint (Max Remanufacturing)
for l in range(1,L): # for each market level
    for k in range(1,P+1): # for each product
        for t in range(2,T): # for each time period
                mdl.add_constraint(mdl.sum(x[a,l+1,k,t] for a in A5 if a[1] in N_r )<= Recovery_max[1]*mdl.sum(x[b,l,k,t] for b in A4), ctname='Recovery2')
            # Transported products to collection/inspection centres should be more than a fraction of products transported to Remanufacturing centres


# 6. Recovering constraint (Max Recycling)
for l in range(1,L): # for each market level
    for k in range(1,P+1): # for each product
        for t in range(2,T): # for each time period
                mdl.add_constraint(mdl.sum(x[a,l+1,k,t] for a in A5 if a[1] in N_y )<= Recovery_max[2]*mdl.sum(x[b,l,k,t] for b in A4), ctname='Recovery3')
            # Transported products to collection/inspection centres should be more than a fraction of products transported to Recycling centres
```

```
#7. To ensure that there should be no product flow in the reverse chain at the first time period.
for i in BN: # for each nodes in backward flow
    for l in range(1,L+1): # for each market level
        for k in range(1,P+1): # for each product
            for t in range(1,T+1): # for each time period
                if t==1: # at the first time period
                    mdl.add_constraint(mdl.sum(x[a,l,k,t] for a in A if a[1]==i)==0,ctname='Backward1')
                     # Transportation flow at the first time period in backward flow should be equal to Zero.


#8. To ensure that there should be no product flow in the reverse chain for the first market level.
for i in IN: # for each nodes in backward flow
    if i not in N_p: #if the origin is not customer centre
        for l in range(1,L+1): # for each market level
            if l==1: # if the market level is equal to one
                for k in range(1,P+1): # for each product
                    for t in range(1,T+1):  # for each time period
                        mdl.add_constraint(mdl.sum(x[a,l,k,t] for a in A if a[1]==i)==0,ctname='Backward2')
                        # Transportation flow for the first market level in backward flow should be equal to Zero.

#9. Forces the model to activate facilities if there is a demand at a market level.
for i in N: # for each node
    for l in range(1,L+1): # for each market level
        for k in range(1,P+1): # for each product
            for t in range(1,T+1):  # for each time period
                mdl.add_constraint(y[i,l,k,t]<=v[l,k],ctname='NodeMarket')
                  # if a  market level is not activated for a certain product, facilities should not be open for that
market level.


# 10. Opened facilities
for i in N: # for each node
    for l in range(1,L+1): # for each market level
        for k in range(1,P+1): # for each product
            for t in range(2,T+1): # for each time period
                mdl.add_constraint(y[i,l,k,t-1]<=y[i,l,k,t],ctname='Node')
                    # If a node established at a certain time period, it should always remain open



# 11. Supply variable for all nodes except from "Supplier" and "Disposal"
for i in N: # for each node
    if i not in N_s: # if the origin is not a supplier
        if i not in N_p: # if the origin is not a disposal centre
            for l in range(1,L+1): # for each market level
                for k in range(1,P+1):  # for each product
                    for t in range(1,T+1): # for each time period
                        mdl.add_constraint((supply[i,l,k,t])==0,ctname='Supply_all')
```

```
# 12. Supply variable for "Disposal"
for i in N_p: # for each diposal centre
    for l in range(1,L+1):  # for each market level
        for k in range(1,P+1):   # for each product
            for t in range(1,T+1):   # for each time period
                mdl.add_constraint((supply[i,l,k,t])<=0,ctname='Supply_Disposal')


# 13. Supply variable for "Supplier" for the first market level
for i in N_s:  # for each supplier
    for l in range(1,L+1): # for each market level
        if l==1:  # if it's the first market
            for k in range(1,P+1):  # for each product
                for t in range(1,T+1):  # for each time period
                    mdl.add_constraint((supply[i,l,k,t])>=0,ctname='Supply_sup1')


# 14. Supply variable for "Supplier" for other market levels
for i in N_s:  # for each supplier
    for l in range(1,L+1): # for each market level
        if l>1: # if it's not the first market
            for k in range(1,P+1): # for each product
                for t in range(1,T+1): # for each time period
                    mdl.add_constraint((supply[i,l,k,t])==0,ctname='Supply_sup2')


# Solving the model

# Set the enuber of threads
mdl.parameters.threads = 10

mdl.print_information()
mdl.minimise_static_lex(exprs=[-Profit,Disposal])
solution = mdl.solve(lex_mipgaps=[0.05, 0.05], log_output=True)
mdl.export_as_lp('U:\ManW10\Downloads\CLSCAZAR')

print(Profit.solution_value)
print (Disposal.solution_value)

max_profit = Profit.solution_value
max_disposal = Disposal.solution_value

mdl.print_information()
mdl.minimise_static_lex(exprs=[Disposal, -Profit])
solution = mdl.solve(lex_mipgaps=[0.05, 0.05], log_output=True)
mdl.export_as_lp('U:\ManW10\Downloads\CLSCAZAR')

print (Profit.solution_value)
print (Disposal.solution_value)
```

```
min_profit = Profit.solution_value
min_disposal = Disposal.solution_value


print ("max disposal", max_disposal)

print ("min disposal", min_disposal)

range_profit = max_profit - min_profit
range_disposal = max_disposal - min_disposal

print ("range for Profit: ", range_profit)
print ("range for disposal: ", range_disposal)


# step_disposal = int(range_disposal/GRIDPOINTS)
step_disposal = max(int(range_disposal/GRIDPOINTS),1)
epsilon = max_disposal

OBJ1= []
OBJ2= []
GP= []
MLEXP= []

Market_level= []
Returned_Products= []
Reused_Products= []
Remanufactured_Products= []
Recycled_Products= []
Disposed_Products= []
Reused_Products_fraction= []
Remanufactured_Products_fraction= []
Recycled_Products_fraction= []
Disposed_Products_fraction= []
Rev=[]
Rev1=[]
Rev2=[]
Rev3=[]
Rev4=[]
Rev5= []
Satisfied_Demand1= []
Satisfied_Demand2= []
Satisfied_Demand3= []
Satisfied_Demand4= []
Satisfied_Demand5= []
Demand1= []
Demand2= []
Demand3= []
```

```
Demand4= []
Demand5= []
Demand_per1= []
Demand_per2= []
Demand_per3= []
Demand_per4= []
Demand_per5= []
Supcos= []
Marcos= []
Fixcos= []
Unicos= []
Supcost_Ratio= []
Marcost_Ratio= []
Fixcost_Ratio= []
Varcost_Ratio= []


gridpointnumber = 0
mdl.add_constraint(Disposal_slack== epsilon,ctname='epsilon')
AUGtime = process_time()-time_start
while (epsilon>=min_disposal) and (AUGtime<=TIMELIMIT):
    gridpointnumber +=1
    mdl.minimise_static_lex(exprs=[-Profit, Disposal])
    mdl.get_constraint_by_name("epsilon").rhs=epsilon
    if mdl.solve(lex_mipgaps=[0.05, 0.05], log_output=True):
        bypass=int(slack.solution_value/max(step_disposal,0.01))
        if (slack.solution_value > step_disposal):
            print (bypass)
        epsilon -= max(step_disposal*(bypass+1),1)
        if bypass > 0:
            for bypassindex in range(gridpointnumber+1, min(gridpointnumber+1+bypass,GRIDPOINTS+1),1):
                Flag[bypassindex]=2



        solution = mdl.solution
        if (Profit.solution_value>0):
            for k in range (1, P+1):
                max_level = 0
                for l in range (1, L+1):
                    for t in range (1, T+1):
                        if solution.get_value(z[l,k,t]) == 1:
                            max_level = max(l,max_level)
                Market_level.append(max_level)


            Returned_Products.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_e for k in
              range(1,P+1) for t in range(1,T+1) for l in range(1,L+1))))
```

```
Reused_Products.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_u for k in
  range(1,P+1) for t in range(1,T+1) for l in range(1,L+1))))

Remanufactured_Products.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_r
  for k in range(1,P+1) for t in range(1,T+1) for l in range(1,L+1))))

Recycled_Products.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_y for k in
  range(1,P+1) for t in range(1,T+1) for l in range(1,L+1))))

Disposed_Products.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_p for k in
  range(1,P+1) for t in range(1,T+1) for l in range(1,L+1))))


Rev1.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==1 for k in range(1,P+1) for t in range(1,T+1))))

Rev2.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==2 for k in range(1,P+1) for t in range(1,T+1))))

Rev3.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==3 for k in range(1,P+1) for t in range(1,T+1) )))

Rev4.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==4 for k in range(1,P+1) for t in range(1,T+1))))

Rev5.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==5 for k in range(1,P+1) for t in range(1,T+1))))


Satisfied_Demand1.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==1 for k in range(1,P+1) for t in range(1,T+1))))

Satisfied_Demand2.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==2 for k in range(1,P+1) for t in range(1,T+1))))

Satisfied_Demand3.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==3 for k in range(1,P+1) for t in range(1,T+1))))

Satisfied_Demand4.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==4 for k in range(1,P+1) for t in range(1,T+1))))

Satisfied_Demand5.append(solution.get_value(mdl.sum(x[a,l,k,t] for a in A if a[1] in N_c for l in
  range(1,L+1) if l==5 for k in range(1,P+1) for t in range(1,T+1))))

Demand1.append(solution.get_value(mdl.sum(Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for q
  in range(l+1,L+1))) for i in range(d+1,c+1) for l in range(1,L+1) if l==1 for k in range(1,P+1) for t in
  range(1,T+1))))
```

```
        Demand2.append(solution.get_value(mdl.sum(Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for
        q in range(l+1,L+1))) for i in range(d+1,c+1) for l in range(1,L+1) if l==2 for k in range(1,P+1) for t
        in range(1,T+1))))
        Demand3.append(solution.get_value(mdl.sum(Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for
        q in range(l+1,L+1))) for i in range(d+1,c+1) for l in range(1,L+1) if l==3 for k in range(1,P+1) for t
        in range(1,T+1))))
        Demand4.append(solution.get_value(mdl.sum(Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for
        q in range(l+1,L+1))) for i in range(d+1,c+1) for l in range(1,L+1) if l==4 for k in range(1,P+1) for t
        in range(1,T+1))))
        Demand5.append(solution.get_value(mdl.sum(Demand[i,l,k,t]*(1-mdl.sum(CE[q,k,t]*z[q,k,t] for
        q in range(l+1,L+1))) for i in range(d+1,c+1) for l in range(1,L+1) if l==5 for k in range(1,P+1) for t
        in range(1,T+1))))


        Sc=mdl.sum(SupplyCost[i-1]*supply[i,l,k,t] for i in N_s for l in range(1,L+1) for k in range(1,P+1)for
        t in range(1,T+1))
        Mc=mdl.sum(mar*v[l,k] for l in range(1,L+1) for k in range(1,P+1))
            Fcc=mdl.sum((FC[i-1]/T)*y[i,l,k,t] for i in N if i not in N_c for l in range(1,L+1) for k in
        range(1,P+1)for t in range(1,T+1))
          Uc=mdl.sum(U_cost[a]*x[a,l,k,t] for a in A for l in range(1,L+1) for k in range(1,P+1)for t in
        range(1,T+1))

        Rev.append(solution.get_value(mdl.sum(Disc[l,k]*Price[k]*x[a,l,k,t] for a in A if a[1] in N_c for l
        in range(1,L+1) for k in range(1,P+1) for t in range(1,T+1))))

    # plt.show()
    OBJ1.append(Profit.solution_value)
    OBJ2.append(Disposal.solution_value)
    GP.append(gridpointnumber)
    MLEXP.append(max_level)


    Supcos.append(Sc.solution_value)
    Marcos.append(Mc.solution_value)
    Fixcos.append(Fcc.solution_value)
    Unicos.append(Uc.solution_value)



    print(solution)
    gridpointnumber += bypass

else:
    # feasibility jumps
    for fb_index in range(gridpointnumber+1,GRIDPOINTS+1,1):
        Flag[fb_index]=1
AUGtime = process_time()-time_start
```

```
def get_number_of_elements(list):
    count = 0
    for element in list:
        count += 1
    return count


OBJ1D=[]
OBJ2D=[]
Market_levelD=[]
Returned_ProductsD=[]
Reused_ProductsD=[]
Remanufactured_ProductsD=[]
Recycled_ProductsD=[]
Disposed_ProductsD=[]
Rev1D=[]
Rev2D=[]
Rev3D=[]
Rev4D=[]
Rev5D=[]
Satisfied_Demand1D=[]
Satisfied_Demand2D=[]
Satisfied_Demand3D=[]
Satisfied_Demand4D=[]
Satisfied_Demand5D=[]
Demand1D=[]
Demand2D=[]
Demand3D=[]
Demand4D=[]
Demand5D=[]



# CHECK DOMINANCE ON SOLUTIONS
distinct_dominant_solutions = 0
for isx in range(0, len(OBJ1)):      # consider the i-th solution
    checkdominance = 0
    for jsx in range(0, len(OBJ1)):  # consider the j-th solution
        if (OBJ1[isx] <= OBJ1[jsx]) and (OBJ2[isx] >= OBJ2[jsx]):  # if at least one criteria is dominant for i
            if (isx != jsx):
                checkdominance += 1
    if checkdominance == 0:
        distinct_dominant_solutions += 1
        OBJ1D.append(OBJ1[isx])
        OBJ2D.append(OBJ2[isx])
        Market_levelD.append(Market_level[isx])
        Returned_ProductsD.append(Returned_Products[isx])
        Reused_ProductsD.append(Reused_Products[isx])
        Remanufactured_ProductsD.append(Remanufactured_Products[isx])
```

```
        Recycled_ProductsD.append(Recycled_Products[isx])
        Disposed_ProductsD.append(Disposed_Products[isx])
        Reused_Products_fraction.append(Reused_ProductsD[isx]/Returned_ProductsD[isx])
         Remanufactured_Products_fraction.append(Remanufactured_ProductsD[isx]/Returned_ProductsD[i
sx])
        Recycled_Products_fraction.append(Recycled_ProductsD[isx]/Returned_ProductsD[isx])
        Disposed_Products_fraction.append(Disposed_ProductsD[isx]/Returned_ProductsD[isx])
        Rev1D.append(Rev1[isx])
        Rev2D.append(Rev2[isx])
        Rev3D.append(Rev3[isx])
        Rev4D.append(Rev4[isx])
        Rev5D.append(Rev5[isx])
        Satisfied_Demand1D.append(Satisfied_Demand1[isx])
        Satisfied_Demand2D.append(Satisfied_Demand2[isx])
        Satisfied_Demand3D.append(Satisfied_Demand3[isx])
        Satisfied_Demand4D.append(Satisfied_Demand4[isx])
        Satisfied_Demand5D.append(Satisfied_Demand5[isx])
        Demand1D.append(Demand1[isx])
        Demand2D.append(Demand2[isx])
        Demand3D.append(Demand3[isx])
        Demand4D.append(Demand4[isx])
        Demand5D.append(Demand5[isx])

        Demand_per1.append(Satisfied_Demand1D[isx]/Demand1D[isx])
        Demand_per2.append(Satisfied_Demand2D[isx]/Demand2D[isx])
        Demand_per3.append(Satisfied_Demand3D[isx]/Demand3D[isx])
        Demand_per4.append(Satisfied_Demand4D[isx]/Demand4D[isx])
        Demand_per5.append(Satisfied_Demand5D[isx]/Demand5D[isx])

        Supcost_Ratio.append(Supcos[isx]/Rev[isx])
        Marcost_Ratio.append(Marcos[isx]/Rev[isx])
        Fixcost_Ratio.append(Fixcos[isx]/Rev[isx])
        Varcost_Ratio.append(Unicos[isx]/Rev[isx])



print(sys.argv[1],end=" ",file=open(output_file_kpi_batch,"a"))
print(sys.argv[2],end=" ",file=open(output_file_kpi_batch,"a"))
print(sys.argv[3],end=" ",file=open(output_file_kpi_batch,"a"))


print(gridpointnumber,end=" ",file=open(output_file_kpi_batch,"a"))

# print the number of non-dominated Pareto solutions
Pareto_solutions=len(OBJ1)
print(Pareto_solutions, end=' ', file = open(output_file_kpi_batch, "a"))

count_feas = 0
count_bypass = 0
```

```
for fb_index in range (1, GRIDPOINTS+1, 1):
   if Flag[fb_index]==1: count_feas += 1
   if Flag[fb_index]==2: count_bypass += 1

print(count_feas,end=' ',file=open(output_file_kpi_batch,"a"))
print(count_bypass,end=' ',file=open(output_file_kpi_batch,"a"))



time_elapsed = (process_time() - time_start)
print ("%5.1f" % (time_elapsed), end=' ',file = open(output_file_kpi_batch, "a"))



if Pareto_solutions==0:
   print("Infeasible_Solution!", end='\n', file = open(output_file_kpi_batch, "a"))
else:

   Max_Obj1=max(OBJ1D)
   Mean_Obj1=sum(OBJ1D)/len(OBJ1D)
   Min_Obj1=min(OBJ1D)
   print(Max_Obj1, end=' ', file = open(output_file_kpi_batch, "a"))
   print(Mean_Obj1, end=' ', file = open(output_file_kpi_batch, "a"))
   print(Min_Obj1, end=' ', file = open(output_file_kpi_batch, "a"))


   Max_Obj2=max(OBJ2D)
   Mean_Obj2=sum(OBJ2D)/len(OBJ2D)
   Min_Obj2=min(OBJ2D)
   print(Max_Obj2, end=' ', file = open(output_file_kpi_batch, "a"))
   print(Mean_Obj2, end=' ', file = open(output_file_kpi_batch, "a"))
   print(Min_Obj2, end=' ', file = open(output_file_kpi_batch, "a"))



   Max_Market=max(Market_levelD)
   Mean_Market=sum(Market_levelD)/len(Market_levelD)
   Median_Market=statistics.median(Market_levelD)
   Min_Market=min(Market_levelD)
   print(Max_Market, end=' ', file = open(output_file_kpi_batch, "a"))
   print(math.ceil(Mean_Market), end=' ', file = open(output_file_kpi_batch, "a"))
   print(math.ceil(Median_Market), end=' ', file = open(output_file_kpi_batch, "a"))
   print(Min_Market, end=' ', file = open(output_file_kpi_batch, "a"))



   Max_Reused=max(Reused_Products_fraction)
```

```
Mean_Reused=sum(Reused_Products_fraction)/len(Reused_Products_fraction)
Min_Reused=min(Reused_Products_fraction)
print(Max_Reused, end=' ', file = open(output_file_kpi_batch, "a"))
print(Mean_Reused, end=' ', file = open(output_file_kpi_batch, "a"))
print(Min_Reused, end=' ', file = open(output_file_kpi_batch, "a"))

Max_Remanufactured=max(Remanufactured_Products_fraction)
 Mean_Remanufactured=sum(Remanufactured_Products_fraction)/len(Remanufactured_Products_frac
tion)
Min_Remanufactured=min(Remanufactured_Products_fraction)
print(Max_Remanufactured, end=' ', file = open(output_file_kpi_batch, "a"))
print(Mean_Remanufactured, end=' ', file = open(output_file_kpi_batch, "a"))
print(Min_Remanufactured, end=' ', file = open(output_file_kpi_batch, "a"))

Max_Recycled=max(Recycled_Products_fraction)
Mean_Recycled=sum(Recycled_Products_fraction)/len(Recycled_Products_fraction)
Min_Recycled=min(Recycled_Products_fraction)
print(Max_Recycled, end=' ', file = open(output_file_kpi_batch, "a"))
print(Mean_Recycled, end=' ', file = open(output_file_kpi_batch, "a"))
print(Min_Recycled, end=' ', file = open(output_file_kpi_batch, "a"))


Max_Disposed=max(Disposed_Products_fraction)
Mean_Disposed=sum(Disposed_Products_fraction)/len(Disposed_Products_fraction)
Min_Disposed=min(Disposed_Products_fraction)
print(Max_Disposed, end=' ', file = open(output_file_kpi_batch, "a"))
print(Mean_Disposed, end=' ', file = open(output_file_kpi_batch, "a"))
print(Min_Disposed, end=' ', file = open(output_file_kpi_batch, "a"))


print(max(Demand_per1), end=' ', file = open(output_file_kpi_batch, "a"))
print(statistics.mean(Demand_per1), end=' ', file = open(output_file_kpi_batch, "a"))

print(max(Demand_per2), end=' ', file = open(output_file_kpi_batch, "a"))
print(statistics.mean(Demand_per2), end=' ', file = open(output_file_kpi_batch, "a"))

print(max(Demand_per3), end=' ', file = open(output_file_kpi_batch, "a"))
print(statistics.mean(Demand_per3), end=' ', file = open(output_file_kpi_batch, "a"))

print(max(Demand_per4), end=' ', file = open(output_file_kpi_batch, "a"))
print(statistics.mean(Demand_per4), end=' ', file = open(output_file_kpi_batch, "a"))

print(max(Demand_per5), end=' ', file = open(output_file_kpi_batch, "a"))
print(statistics.mean(Demand_per5), end=' ', file = open(output_file_kpi_batch, "a"))
```

B. INSTANCE GENERATOR

```
import numpy as np                    # A library for the mathematical functions
import docplex.mp.model as cpx      # CPLEX solver
import random as rnd

classes = 3
random_repetitions= 10

#Number of facilities
class_facilities = 9

# Constant Demand
D0=3000


# Range of Prices
Price_min = [15000]
Price_max = [20000]


# Unit variable costs for forawrd and backward flow
VariableCost_min = [100,10]
VariableCost_max = [1000,100]

#Supply cost
supcos_min=100
supcos_max=1000


# Number of facilities in different sizes of problems
nsuppliers=[2,4,6,8,10,12,14,16,18,20,22,24,26,28,30]
nmanufacturers=[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15]
ndistributors=[3,6,9,12,15,18,21,24,27,30,33,36,39,42,45]
ncustomers=[6,12,18,24,30,36,42,48,54,60,66,72,78,84,90]
ncollectors=[3,6,9,12,15,18,21,24,27,30,33,36,39,42,45]
nupgraders=[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15]
nremanufacturers=[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15]
nrecyclers=[2,4,6,8,10,12,14,16,18,20,22,24,26,28,30]
ndisposals=[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15]
# Number of nodes

# THESE ARE GONNNA CHANGE ON THE CLASSS OF INSTANCES
for class_index in range(1,classes+1):
                  Number_of_nodes=nsuppliers[class_index-1]+nmanufacturers[class_index-
               1]+ndistributors[class_index-1]+ncustomers[class_index-
               1]+ncollectors[class_index-1]+nupgraders[class_index-
```

```
                    1]+nremanufacturers[class_index-1]+nrecyclers[class_index-
                    1]+ndisposals[class_index-1]
    ForNodes=nsuppliers[class_index-1]+nmanufacturers[class_index-1]+ndistributors[class_index-
                1]+ncustomers[class_index-1]
  BackNodes=ncollectors[class_index-1]+nupgraders[class_index-1]+nremanufacturers[class_index-
              1]+nrecyclers[class_index-1]+ndisposals[class_index-1]
Customer_centres= ncustomers[class_index-1]

for repetition_index in range(1,random_repetitions+1):

  instance_file = "instance_%d_%d.py" % (class_index, repetition_index)

  print("Supplier=", nsuppliers[class_index-1], file = open(instance_file, "a"))
  print("Manufacturer=", nmanufacturers[class_index-1], file = open(instance_file, "a"))
  print("Distributor=",ndistributors[class_index-1] ,file = open(instance_file, "a"))
  print("Customer=", ncustomers[class_index-1],file = open(instance_file, "a"))
  print("Collector=", ncollectors[class_index-1],file = open(instance_file, "a"))
  print("Upgrader=", nupgraders[class_index-1],file = open(instance_file, "a"))
  print("Remanufacturer=", nremanufacturers[class_index-1],file = open(instance_file, "a"))
  print("Recycler=", nrecyclers[class_index-1],file = open(instance_file, "a"))
  print("Disposal=", ndisposals[class_index-1],file = open(instance_file, "a"))


  s=nsuppliers[class_index-1]        # Suppliers
  m=s+nmanufacturers[class_index-1]   # Manufacturers
  d=m+ndistributors[class_index-1]    # Distributers
  c=d+ncustomers[class_index-1]       # Customer centres
  e=c+ncollectors[class_index-1]      # Collection and inspection centres
  u=e+nupgraders[class_index-1]       # Reusing centres
  r=u+nremanufacturers[class_index-1] # Remanufacturing centres
  y=r+nrecyclers[class_index-1]       # Recycling centres
  w=y+ndisposals[class_index-1]       # Disposal centres


  """Sets"""
  N_s =[i for i in range(1,s+1)]   # Set of suppliers
  N_m =[i for i in range(s+1,m+1)] # Set of Manufacturers
  N_d =[i for i in range(m+1,d+1)] # Set of Distributers
  N_c =[i for i in range(d+1,c+1)] # Set of Customer centres
  N_e =[i for i in range(c+1,e+1)] # Set of Collection and inspection centres
  N_u =[i for i in range(e+1,u+1)] # Set of Reusing centres
  N_r =[i for i in range(u+1,r+1)] # Set of Remanufacturing centres
  N_y =[i for i in range(r+1,y+1)] # Set of Recycling centres
  N_p =[i for i in range(y+1,w+1)] # Set of Disposal centres


  # Nodes
  N= N_s + N_m + N_d + N_c + N_e + N_u + N_r+ N_y + N_p   # All nodes
  BN= N_e + N_u + N_r + N_y + N_p                       # Backward Nodes
```

```
IN= N_u + N_r + N_y + N_p                    # Treatment Nodes


#Arcs
A1=[(i,j) for i in N_s for j in N_m]    # Arc from Supplier to Manufacturing centre
A2=[(i,j) for i in N_m for j in N_d]    # Arc from Manufacturing centre to Distribution centre
A3=[(i,j) for i in N_d for j in N_c]    # Arc from Distribution centre to Customer centre
A4=[(i,j) for i in N_c for j in N_e]    # Arc from Customer centre to Collection/inspection centre
A5=[(i,j) for i in N_e for j in N_u]    # Arc from Collection/inspection centre to All the recovering centres
A6=[(i,j) for i in N_e for j in N_r]    # Arc from Collection/inspection centre to All the recovering centres
A7=[(i,j) for i in N_e for j in N_y]    # Arc from Collection/inspection centre to All the recovering centres
A8=[(i,j) for i in N_e for j in N_p]    # Arc from Collection/inspection centre to All the recovering centres
A9=[(i,j) for i in N_y for j in N_s]    # Arc from Recycling centre to supplier
A10=[(i,j) for i in N_r for j in N_m]   # Arc from Remanufacturing centre to Manufacturing plants
A11=[(i,j) for i in N_u for j in N_d]   # Arc from Upgrade/Reusing centre to Distribution centre
A=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11    # All arcs through the network
FA=A1+A2+A3
CA=A1+A2+A3+A4
RUA1=A1+A2+A3+A4+A5
RMA1=A1+A2+A3+A4+A5+A6
RYA1=A1+A2+A3+A4+A5+A6+A7
DPA=A1+A2+A3+A4+A5+A6+A7+A8
RYA2=A1+A2+A3+A4+A5+A6+A7+A8+A9
RMA2=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10
RUA2=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11

print("classes=", classes, file = open(instance_file, "a"))
print("random_repetitions=", random_repetitions, file = open(instance_file, "a"))


# generate the number of market levels
lnumber = rnd.randint(5,5)
print("L=", lnumber, file = open(instance_file, "a"))

# Generate the number of products
pnumber = rnd.randint(1,1)
print("P=", pnumber, file = open(instance_file, "a"))

# Generate nuber of time periods
tnumber =15
print("T=",tnumber, file = open(instance_file, "a"))


# Fixed cost of establishing each facility
fixed_cost=[]
print("FC=", end = '', file = open(instance_file, "a"))
for fxc in range(nsuppliers[class_index-1]):
    fixcost = rnd.randint(70000000,150000000)
    fixed_cost.append(fixcost)
```

```
for fxc in range(nmanufacturers[class_index-1]):
   fixcost = rnd.randint(70000000,150000000)
   fixed_cost.append(fixcost)
for fxc in range(ndistributors[class_index-1]):
   fixcost = rnd.randint(1000000,2000000)
   fixed_cost.append(fixcost)
for fxc in range(ncustomers[class_index-1]):
   fixcost = rnd.randint(0,0)
   fixed_cost.append(fixcost)
for fxc in range(ncollectors[class_index-1]):
   fixcost = rnd.randint(100000,1000000)
   fixed_cost.append(fixcost)
for fxc in range(nupgraders[class_index-1]):
   fixcost = rnd.randint(100000,1000000)
   fixed_cost.append(fixcost)
for fxc in range(nremanufacturers[class_index-1]):
   fixcost = rnd.randint(100000,1000000)
   fixed_cost.append(fixcost)
for fxc in range(nrecyclers[class_index-1]):
   fixcost = rnd.randint(100000,1000000)
   fixed_cost.append(fixcost)
for fxc in range(ndisposals[class_index-1]):
   fixcost = rnd.randint(100000,1000000)
   fixed_cost.append(fixcost)
print (fixed_cost, end =  '\n', file = open(instance_file, "a"))


# Range of Capacity levels
Capacity=[]
print("Cpy=", end = '', file = open(instance_file, "a"))
for cpy in range(nsuppliers[class_index-1]):
   facility_capacity = rnd.randint(18000,42000)
   Capacity.append(facility_capacity)
for cpy in range(nmanufacturers[class_index-1]):
   facility_capacity = rnd.randint(6000,14000)
   Capacity.append(facility_capacity)
for cpy in range(ndistributors[class_index-1]):
   facility_capacity = rnd.randint(6000,14000)
   Capacity.append(facility_capacity)
for cpy in range(ncustomers[class_index-1]):
   facility_capacity = rnd.randint(1000000000,1000000000)
   Capacity.append(facility_capacity)
for cpy in range(ncollectors[class_index-1]):
   facility_capacity = rnd.randint(6000,14000)
   Capacity.append(facility_capacity)
for cpy in range(nupgraders[class_index-1]):
   facility_capacity = rnd.randint(3000,7000)
   Capacity.append(facility_capacity)
for cpy in range(nremanufacturers[class_index-1]):
```

```
    facility_capacity = rnd.randint(3000,7000)
    Capacity.append(facility_capacity)
for cpy in range(nrecyclers[class_index-1]):
    facility_capacity = rnd.randint(9000,21000)
    Capacity.append(facility_capacity)
for cpy in range(ndisposals[class_index-1]):
    facility_capacity = rnd.randint(6000,14000)
    Capacity.append(facility_capacity)
print (Capacity, end =  '\n', file = open(instance_file, "a"))



# Cannibalisation ratio at each market level
print("cae=[0,0.4,0.3,0.2,0.1]", file = open(instance_file, "a"))


# Discounting price for L_ary market level
print("iii = [1,0.8,0.7,0.6,0.5]", file = open(instance_file, "a"))

#Range of recovering centres
print("Recovery_min=[0.35,0.28,0.22]", file = open(instance_file, "a"))
print("Recovery_max=[0.39,0.34,0.29]", file = open(instance_file, "a"))


# Ranges of Product prices
print("Prod_Price=[", end = '', file = open(instance_file, "a"))
for i in range(1,pnumber+1):
    print (rnd.randint(Price_min[i-1],Price_max[i-1]), end =  '', file = open(instance_file, "a"))
    if i < pnumber:
        print (end =  ',', file = open(instance_file, "a"))
print("]", file = open(instance_file, "a"))


# Delay from returning the EoL products
Delay_of_return=[0,1]

print("Dly=[", end = '', file = open(instance_file, "a"))
for i in range(1,3):
    if i==1:
        print (Delay_of_return[0], end =  '', file = open(instance_file, "a"))
    if i==2:
        print (Delay_of_return[1], end =  '', file = open(instance_file, "a"))
    if i < 2:
        print (end =  ',', file = open(instance_file, "a"))
print("]", file = open(instance_file, "a"))

# Downgrade level of EoL products
print("Dwngrd=[0,1]", file = open(instance_file, "a"))
```

```
# Variable cost at each arc
unit_variable_cost=[]
print("unit_cost=", end = '', file = open(instance_file, "a"))
for xx in range(1,len(A)+1):
    if xx in range(1,len(FA)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(CA)+1,len(RUA1)+1):
        uvc = rnd.randint(0,0)
        unit_variable_cost.append(uvc)
    elif xx in range(len(RUA1)+1,len(RMA1)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(RMA1)+1,len(RYA1)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(RYA1)+1,len(DPA)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(DPA)+1,len(RYA2)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(RYA2)+1,len(RMA2)+1):
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
    elif xx in range(len(RMA2)+1,len(RUA2)+1):
        uvc = rnd.randint(0,0)
        unit_variable_cost.append(uvc)
    else:
        uvc = rnd.randint(VariableCost_min[0],VariableCost_max[0])
        unit_variable_cost.append(uvc)
print (unit_variable_cost, end = '\n', file = open(instance_file, "a"))


#unit supply cost
unit_supply_cost=[]
print("SupplyCost=", end = '', file = open(instance_file, "a"))
for i in range(1,Number_of_nodes+1):
    sppc = rnd.randint(supcos_min,supcos_max)
    unit_supply_cost.append(sppc)
print (unit_supply_cost, end = '\n', file = open(instance_file, "a"))


# Customer Demand
Customer_demand=[]
print("Dd=[", end = '',file = open(instance_file, "a"))
for i in range(1,Customer_centres+1):
    for l in range(1,lnumber+1):
        if l==1:
```

```
            print("[[[", end = '', file = open(instance_file, "a"))
          else:
            print("[[", end = '', file = open(instance_file, "a"))
          for k in range(1,pnumber+1):
            for t in range(1,tnumber+1):
              Demand = D0+int((rnd.randint(-0.1*D0,0.1*D0)))
              Customer_demand.append(Demand)
              print (Customer_demand[t-1], end =  '', file = open(instance_file, "a"))
              if t < tnumber:
                print (end =  ',', file = open(instance_file, "a"))
            if l==lnumber and i < Customer_centres:
              print("]]]", end = ', \n', file = open(instance_file, "a"))
            elif l==lnumber and i == Customer_centres:
              print("]]]", end = '', file = open(instance_file, "a"))
            else:
              print("]]", end = ', \n', file = open(instance_file, "a"))
      print("]", end = '', file = open(instance_file, "a"))
```

C. BASH SCRIPT (TO RUN EXPERIMENTS ON THE SERVER)

```
#!/bin/bash
for filename in ./instance*.py;
  do
    f="$(basename -- $filename)"
    echo -e "$f"
    for k in 20;
    do
      for ((fcml=50000000; fcml<=250000000; fcml+=50000000))
      do
        python3.8 ./scriptclsc-Costs.py $f $k $fcml
      done
    done
  done

#here we run experiments with market level activation costs from 50 to 250 millions and 20 grid points
```

APPENDIX 3: DOCTORAL DEVELOPMENT PORTFOLIO

SUMS MGT6225 and FCS6100 modules

Code	Module	Status
MGT6225	Unfair means and plagiarism	29 October 2019
MGT6225	Finding a research question	05 February 2020

MGT6225	Introduction to Social Theory	Cancelled; I reviewed the materials uploaded on Blackboard.
MGT6225	Designing your methodology	Cancelled; I reviewed the materials uploaded on Blackboard.
MGT6225	Preparing for Teaching at SUMS	7 May 2020
MGT6225	Preparing for your confirmation review	12 May 2020
MGT6225	Social Theory for ODMS	26 May 2020
FCS6100	Research Ethics Introductory lecture	5 February 2020
MGT6225	Doing a Literature Review	28 January 2021 (Part 1); 4 February 2021 (Part 2)
MGT6225	Preparing for Publication	26 May 2021
MGT6225	Building a researcher profile	27 January 2022
FCS6100	Research Ethics and Integrity	11 March 2022
MGT6225	Transitioning out of your PhD	16 March 2022
MGT6225	Assessment Information Briefing	13 May 2022
MGT6225	Preparing for the VIVA	9 June 2022

Conferences/other Training activities within UoS/SUMS/OMDS

Workshop/Training	Date
SUMS' Annual Doctoral Conference	18 September 2019
Python programming training Course	26 September 2019
Tools for literature searching	8 October 2019
Faculty of Social Sciences – PGR induction session	16 October 2019
Thesis writing course: Principles and Practice	17 October 2019
Speaking Skills for Research Purposes course	25 October 2019
MIES Research Seminar: Application of mixed-methods	1 November 2019
Workshop on Basic statistical principles and SPSS	8 January 2020
Workshop on Approaches to Qualitative Analysis	22 January 2020
JSCM Virtual Methods Series: Analysing and Theorizing Supply Networks	18 February 2021
MGT6085 Global Supply Chain Leadership	22 February 2021
Workshop in Decision Making Methods and Techniques	24 February 2021
JSCM Virtual Methods Series: Case study methods in practice	25 February 2021

OMDS Research Development Event with Dr. Jon Burchell	9 March 2021
PGR - OMDS Virtual Conference	7 December 2021
Practicing Presenting Session	7 January 2022
Presenting Your Research at a Conference	9 March 2022
Networking workshop	5 April 2022
OMDS Research Centre: 'Fast Fashion, Charities, and the Circular Economy: Challenges for Operations Management'	23 June 2022

A. Conferences/other Training activities outside UoS

Conferences /Training courses	**Location**	**Date**
OR Society's Annual Conference (OR64)	University of Warwick, Warwick, UK	13-15 September 2022
International Conference on Resource Sustainability	University College Dublin, Ireland	30 June - 2 July 2020
21st International Working Seminar on Production Economics	Innsbruck, Austria	24-28 February 2020
8th International Workshop – Advances in Cleaner Production	Sanya, China	13-15 November 2019
OR61: Annual Conference	University of Kent, Canterbury, UK	3-5 September 2019
Simulation course	Loughborough University	1– 5 July 2019
Combinatorial Optimisation course	The University of Southampton	9-13 September 2019
Heuristics & Approximation Algorithms	Lancaster University	22-27 June 2020
Stochastic Modelling course	Lancaster University	12-16 April 2021

B. Outreach & Communication activities (see Research Dissemination at the beginning of the thesis)

- **Videos:**

- Circular Economy-led closed loop supply chains - Azar MahmoumGonbadi, The University of Sheffield - YouTube

- Models and methods for the design of Circular Supply Chains - Azar MahmoumGonbadi, UK - YouTube

- **Blog posts:**

- http://www.retrace-itn.eu/2021/07/23/empowering-the-circular-economy/
- http://www.retrace-itn.eu/2020/11/03/you-may-want-to-change-the-way-you-buy clothes/
- http://www.retrace-itn.eu/2020/06/11/the-virtual-retrace-roundtable-for-industryand-policy-makers/

APPENDIX 4: DATA MANAGEMENT PLAN (DMP)

Designing Closed-loop Supply Chains for the transition towards a Circular Economy: Models, Methods and Applications

A Data Management Plan created using DMPonline

Creator: Azar MahmoumGonbadi

Affiliation: The University of Sheffield

Funder: European Commission (Horizon 2020)

Template: Horizon 2020 DMP

Grant number: 814247

Project abstract:

Awareness towards environmental pollution and the need to achieve resource efficiency has inspired a significant interest towards the adoption of Closed-Loop Supply Chain (CLSC) practices, which can help to address these issues. In the scientific literature, significant attention has been devoted to CLSC network design problems over the past decade regarding the economic, environmental and social attractive; the proposed solutions to these problems are aimed at providing decision support for ensuring the appropriate configuration of supply chains. While the literature in this field is starting to become abundant, several gaps can be identified. One of the most notable ones is the lack of a simultaneous and rigorous assessment of the economic, environmental and social sustainability performances within CLSC design problems. Indeed, in existing papers, the social dimension of sustainability is seldom evaluated; also, the environmental dimension is generally measured in generic ways (CO2 emissions) and not through a rigorous account of the degree of circularity of the devised configurations. Moreover, the integration of strategic, tactical and operational decisions is scarcely studied. This paper will report about these gaps and propose mathematical modelling of a CLSC network to fulfil them. This study aims to propose a multi-objective, multi-commodity, multi-echelon, and multi-period sustainable closed-loop network design model, which considers distinctive recovery options simultaneously, such as reusing, refurbishing, remanufacturing and recycling. This research is motivated by the three P's—people, planet and profit to design a closed-loop supply chain with simultaneous consideration of regions, facility location-allocation and multi-level markets. The adaptability of the proposed mathematical model to real-world case studies will be investigated.

Last modified: 30-08-2020

Designing Closed-loop Supply Chains for the transition towards a Circular Economy: Models, Methods and Applications - Initial DMP

1. Data summary

Provide a summary of the data addressing the following issues:

- **State the purpose of the data collection/generation**
- **Explain the relation to the objectives of the project**
- **Specify the types and formats of data generated/collected**
- **Specify if existing data is being re-used (if any)**
- **Specify the origin of the data**
- **State the expected size of the data (if known)**
- **Outline the data utility: to whom will it be useful**

- **The purpose of the data collection/generation:** validate the proposed conceptual mathematical model and verify the solution approaches and test hypotheses to unveil the role of circular economy (CE) concept in practical closed-loop supply chains.
- **The relation to the objectives of the project:** validate the literature-based framework through semi-structured interviews with ReTraCE experts as well as project partners.
- **The types and formats of data generated/collected:**

- Audio (.mp3), Notes (.docx): Data collection from semi-structured interviews with ReTraCE experts and partners are firstly recorded as an Mp3 file and then interpreted into a word document.
- (excel, Mendeley): Data collection from secondary data sources and published journal articles are reviewed and codified in Microsoft excel. All the secondary sources are collected and organised in Mendeley.

- **The origin of the data:** The developed mathematical model will be applied to companies through a secondary database and Primary data which will be obtained by liaising with ReTraCE project partners.
- **Data utility:** The collected data will be utilised in the data analysis process, to prove the hypothesised link between the literature and empirical data. Data and results will be shared with the ReTraCE project and could be made publicly available.

2. FAIR data

2.1 Making data findable, including provisions for metadata:

- **Outline the discoverability of data (metadata provision)**
- **Outline the identifiability of data and refer to standard identification mechanism. Do you make use of persistent and unique identifiers such as Digital Object Identifiers?**
- **Outline naming conventions used**
- **Outline the approach towards search keyword**
- **Outline the approach for clear versioning**
- **Specify standards for metadata creation (if any). If there are no standards in your discipline describe what metadata will be created and how**

A data collection protocol will be disseminated in the research project.

All the information including the structure of the folder, the methodology for gathering the data, the assumptions, the used variables, the units of measurement, the format and the file type of the data and the software used to collect and/or process the data will be kept in Readme.txt files.

File names will be succinct but meaningful and consistent across versions. A coherent data format will be part of the file name.

2.2 Making data openly accessible:

- **Specify which data will be made openly available? If some data is kept closed provide rationale for doing so**
- **Specify how the data will be made available**
- **Specify what methods or software tools are needed to access the data? Is documentation about the software needed to access the data included? Is it possible to include the relevant software (e.g. in open source code)?**
- **Specify where the data and associated metadata, documentation and code are deposited**
- **Specify how access will be provided in case there are any restrictions**

Access is restricted only to the researchers who directly involved in the project and the supervisory board.

As part of the ReTraCE project, part of the research data will be shared with the other researchers in the consortium. Collaboration within the project researchers is encouraged. A confidentiality agreement is included in the Grant and Consortium Agreement signed by the project partners. No external collaborating/partner organisation or service providers are included. All data will be anonymised.

As suggested by the European Commission, when possible, research generated data will be made available to the research community: part of the research project deals with the creation of a database of circular economy practices adopted in the most important European enterprises, which will be created by codifying information that is already publicly available in company reports or other sources. The database has the potential of becoming open-source, being shared with the research community, and updated yearly. The feasibility of such a project will be considered in the final part of the PhD and will be done in accordance with the EC guidelines.

2.3 Making data interoperable:

- **Assess the interoperability of your data. Specify what data and metadata vocabularies, standards or methodologies you will follow to facilitate interoperability.**
- **Specify whether you will be using standard vocabulary for all data types present in your data set, to allow inter-disciplinary interoperability? If not, will you provide mapping to more commonly used ontologies?**

Metadata will be created to facilitate reusing of data. The research protocol will be made available and stored with the data. The protocol will include: how the data collection and analysis process has been conducted, the software used in the analysis, the assumptions made, and the variables used.

2.4 Increase data re-use (through clarifying licenses):

- **Specify how the data will be licenced to permit the widest reuse possible**
- **Specify when the data will be made available for re-use. If applicable, specify why and for what period a data embargo is needed**
- **Specify whether the data produced and/or used in the project is useable by third parties, in particular after the end of the project? If the re-use of some data is restricted, explain why**
- **Describe data quality assurance processes**
- **Specify the length of time for which the data will remain re-usable**

The gathering data will be reusable after implementing the research in a real-world case problem.

3. Allocation of resources

Explain the allocation of resources, addressing the following issues:

- **Estimate the costs for making your data FAIR. Describe how you intend to cover these costs**
- **Clearly identify responsibilities for data management in your project**
- **Describe costs and potential value of long term preservation**

All the data will be stored on the password-protected University Google drive.
Interview data (recordings, transcriptions, written-form consents) will be anonymised and stored on the password-protected University Google drive.
A copy of all collected data will be stored on the University of Sheffield storage area network for a further 60 months after the end of the project, to allow further analysis and possible publications. Afterwards, data will be destroyed.

4. Data security

Address data recovery as well as secure storage and transfer of sensitive data

The research project does not deal with sensible data.
All data being utilised for research purposes within the project will be anonymised and will not be making any reference to personal characteristics.
The consortium will comply with national and EU legislation on the protection of personal data.
Following face-to-face interviews aim towards obtaining more insights related to the company operations of each respondent in alignment with the survey questions. Consequently, it does not involve the collection and/or processing of sensitive personal data (e.g. health, sex, ethnic origin, political opinions, religious or philosophical beliefs). In addition, it neither involves tracking or observation of participants nor processing of genetic information. All transcripts will be in MS Word .doc format.

5. Ethical aspects

To be covered in the context of the ethics review, ethics section of DoA and ethics deliverables. Include references and related technical aspects if not

covered by the former

Ethical considerations have been integrated in the ethics application.

6. Other

Refer to other national/funder/sectorial/departmental procedures for data management that you are using (if any)

Question not answered.

APPENDIX 5: ETHICS APPLICATION

The University Of Sheffield.

Application 030629

Section A: Applicant details

Date application started:
Thu 8 August 2019 at 11:55

First name:
Azar

Last name:
Mahmoum Gonbadi

Email:
a.mahmoum@sheffield.ac.uk

Generic research application:
No
Last updated:
24/12/2019

Department:
Management School

Applying as:
Staff member

Research project title:
Modelling a holistic Closed-loop Supply Chain (CLSC) network design based on circular economy concepts

Has your research project undergone academic review, in accordance with the appropriate process?
Yes

Similar applications:
- not entered -

Section B: Basic information

Co-Applicants(s)

Name	Email
Andrea Genovese	a.genovese@sheffield.ac.uk

Proposed project duration

Start date (of data collection):
Fri 18 October 2019

Anticipated end date (of project)
Mon 31 October 2022

3: Project code (where applicable)

Project code
814247

Suitability

Takes place outside UK?
Yes

Involves NHS?
No

Health and/or social care human-interventional study?
No

ESRC funded?
No

Likely to lead to publication in a peer-reviewed journal?
Yes

Led by another UK institution?
No

Involves human tissue?
No

Clinical trial or a medical device study?
No

Involves social care services provided by a local authority?
No

Involves adults who lack the capacity to consent?
No

Involves research on groups that are on the Home Office list of 'Proscribed terrorist groups or organisations?
No

Indicators of risk

Involves potentially vulnerable participants?
No
Involves potentially highly sensitive topics?
No

Section C: Summary of research

1. Aims & Objectives

Recently, a growing concern has been raised about the environmental and social impact of companies and business operations. Since products are traditionally landfilled or burned at the end of their life cycle, the landfill and incineration capacities have been significantly reduced by the growing population in the world. Hence the increasing consumption of the limited resources and disposal capacities make the waste disposal problem to become considerably important. Therefore, companies have become aware of the importance of returning policies and remanufacturing products and try to reduce their consumption in order to maintain the irreversible resources as well as the land usage for the future generations. To this end, supply chain issues specially green supply chain management (GSCM) and closed-loop supply chains (CLSC) have become very popular topics for researchers with the aim of incorporating environmental concerns into the various levels of management practices. In this domain, a new concept spread worldwide which is called "circular economy". Circular economy (CE) is concerned with declining the environmental use as well as making self-sustaining products in which materials are used over time. This research aims to propose a multi-objective closed-loop supply chain with CE elements.
The growing desire to obtain the up-to-date information is powered by consumers in the whole supply chain. For this reason, Information management is crucial to forming an efficient CLSC model. In the last decades, novelties in information technology have been employed to provide more timely and precise information in order to match supply with demand and to reduce the uncertainties and divergence between them. The process of information sharing and IT solutions in CLSCs seems to be insufficient for managing the inventory of returned products. Information sharing for managing reverse flows is significant as when the demand and inventory visibility for recovery of products are meager, the result will be an incompatibility demand for and supply of products for remanufacturing such that may have disastrous environmental and economic consequences.

participation, they will be informed that their participation will be on voluntary basis, and anonymity and confidentiality of the participants were maintained at all times. In any face-to-face interviews, each participant will be given a copy of the informed consent statement, followed by a short questionnaire (as reported in Section F). Participants will be able to opt-out of being recorded during the interviews at any point of time, and also not to respond to questions they do not wish to respond to. Contact details of the lead researcher and the supervisory team will also be included. A copy of information sheet and consent form can be found in the supporting documentation section.

4. Payment

Will financial/in kind payments be offered to participants? No

5. Potential Harm to Participants

What is the potential for physical and/or psychological harm/distress to the participants?

This research has no potential of causing any physical or psychological harm on the participants. It poses no risk to participants safety and well-being as it does not involve any clinical trials or any other activity that may require any physical intervention. In addition, the research does not involve invasive methods. Research aim and objectives are not related to sensitive issues such as sex, religion or cultural aspects that may raise confidential personal issues or may intrude participant’s comfort and privacy. In any case, participants are free to withdraw from the research at their personal convenience without giving any reason.

How will this be managed to ensure appropriate protection and well-being of the participants?

Participants will be given an information sheet that explains that they can withdraw from the study at any time and they do not have to give any reasons for why they no longer want to take part. Should a participant express any concern after having agreed to take part in the study, we will immediately pause the consultation and the audio recorder, where applicable. The research team will then remind the participant that they can withdraw their participation if they wish and that they can contact the team again afterwards.Moreover, in order to handle issues unrelated to the project such as illegal activities and so on, we can provide some formal letter confirmation from The University of Sheffield which would be trustful.

Section E: About the data

1. Data Processing

Will you be processing (i.e. collecting, recording, storing, or otherwise using) personal data as part of this project? (Personal data is any information relating to an identified or identifiable living person).
Yes

Which organisation(s) will act as Data Controller?

University of Sheffield only

2. Legal basis for processing of personal data

The University considers that for the vast majority of research, 'a task in the public interest' (6(1)(e)) will be the most appropriate legal basis. If, following discussion with the UREC, you wish to use an alternative legal basis, please provide details of the legal basis, and the reasons for applying it, below:

Not applicable

Will you be processing (i.e. collecting, recording, storing, or otherwise using) 'Special Category' personal data?
No

3. Data Confidentiality

What measures will be put in place to ensure confidentiality of personal data, where appropriate?

As mentioned in the previous sections, data collection will be done by semi-structured ten 15 minutes interviews. Thus, collected data will be both quantitative (Likert scale numerical values ranging from 1-7) and qualitative (in the form of transcripts). No personal data will be collected. The interviews will be related to the demographic profile of the respondent with respect to the interviewed firm’s market type (supply chain stage), product, size (number of employees), age of the company and the respondent’s work position.

With regard to the quantitative strand, collected data is confined to Likert scale (1-7), thus it includes no personal information. Since we respect the confidentiality of the data (i.e: financial), that we want to gather from industries, all data being utilised for research purposes within the project will be anonymised (it means for instance, we will not spread

the name of the industries or the interviewed person) and will not be making any reference to personal characteristics.
The consortium will comply with national and EU legislations on protection of personal data.
Following face-to-face interviews aim towards obtaining more insights related to the company operations of each respondent. Consequently, it does not involve the collection and/or processing of sensitive personal data (e.g. health, sex, ethnic origin, political opinions, religious of philosophical beliefs). In addition, it neither involves tracking or observation of participants nor processing of genetic information. All transcripts will be in MS Word .doc format.

4. Data Storage and Security

In general terms, who will have access to the data generated at each stage of the research, and in what form

Access is restricted only to the researchers directly involved in the project and the supervisory team.
A data collection protocol will be circulated.
A confidentiality agreement is included in the Grant and Consortium Agreement signed by the project partners.
No external collaborating/partner organisation or service providers are included.
In addition, no transcription/translation services will be required as relative procedures, where needed, will be conducted by researchers members of the project in the related country. In order to respect the confidentiality of the participants in interviews and surveys, all data (i.e: financial, strategic and so on) will be anonymised.

What steps will be taken to ensure the security of data processed during the project, including any identifiable personal data, other than those already described earlier in this form?

With respect to data storage and security, all practices with respect to protect information, protecting personal data and protecting research data will be followed, as per University of Sheffield's guidelines. Data analysis and collection training will be completed by the researchers and partners of the consortium.

Will all identifiable personal data be destroyed once the project has ended?
Yes

Please outline when this will take place (this should take into account regulatory and funder requirements).

A copy of all collected data will be stored on the University of Sheffield storage area network for a further 60 months after the end of the project, to allow further analysis and possible publications. Afterwards, data will be destroyed.

Section F: Supporting documentation

Information & Consent

Participant information sheets relevant to project?
Yes

Document 1069972 (Version 4)	All versions
Document 1074362 (Version 1)	All versions

Consent forms relevant to project?
Yes

Document 1069976 (Version 3)	All versions
Document 1074364 (Version 1)	All versions

Additional Documentation

External Documentation

- not entered -

Section G: Declaration

Signed by:
Azar MahmoumGonbadi

APPENDIX 6: TRAINING NEED ANALYSIS

FACULTY OF SOCIAL SCIENCES: TRAINING NEEDS ANALYSIS (TNA)

The skills and experience you should gain by the end of your higher degree studies.

Name of student: **Azar MahmoumGonbadi**
Department or School: **Operations Management and Decision Sciences Division, Sheffield University Management School**
Names of all supervisors: **Prof. Andrea Genovese, Dr. Antonino Sgalambro**
Year of study: **1st year (2019/2020)**

Completing your TNA

Before completing your TNA in consultation with your supervisor(s), you should read the guidance notes that accompany this form.

The Faculty's TNA form has been compiled with reference to the Vitae Researcher Development Framework (RDF), which divides into four 'Domains' the skills, and attitudes and behaviours required to be an effective researcher. The framework is also recognized widely outside academia, and can provide you with an effective way of articulating your skills to employers.

To familiarise yourself with the terms used in the Researcher Development Framework and this form, please, find guidance here.

Prioritising your training and development

Academic, professional and personal development are all key aspects of your doctoral research experience, and the Faculty will support you to develop your skills throughout the course of your PhD. However, time is a precious resource, so it is important to ensure that you undertake the right training at the right stage of your PhD. When considering the twelve areas (three within each 'Domain') in the following table, please decide – in consultation with your supervisor(s) – to what extent it is a priority for the coming year (low, medium or high).

Formal training (such as that within the Faculty of Social Science Core Programme) may be part of your development, but many of the skills required of an effective researcher will also be developed through the process of working on your PhD itself (e.g. developing your critical thinking through writing thesis chapters). Through discussion with your supervisor(s), you should use this form to set realistic goals and identify the action to achieve them – you can then use this to reflect on your development throughout the year.

In addition, remember to keep an up-to-date record of the training you have undertaken within your PhD, as, at the end of your doctoral studies. you will need to submit a

- List of training courses attended (both within and without the University)
- List of completed and submitted items of work (e.g. Literature review)
- List of seminars and conferences attended and whether you presented at these
- List of any outreach activities undertaken
- List of any extracurricular activities you wish to note

RDF Domain A: Knowledge and Intellectual Abilities the knowledge, intellectual abilities and techniques to do research		
	Reflection on your current ability/experience in this area and main priorities for the coming year	**Action to be taken to develop this area (if appropriate), agreed with your supervisor(s).**

Knowledge base (RDF subdomain A1) Including: - Subject knowledge - Research methods – theoretical knowledge and practical application - Information seeking and information management skills - Academic literacy and numeracy	- I gained the basic knowledge of logistic and supply chain issues during my bachelor and master's level. However, I wish to develop my thorough understanding of closed-loop supply chain problems with more details. - Despite my core knowledge about methodologies and techniques relevant to supply chain problems, I would like to gain more understanding within this area. - I became familiar with how to perform an appropriate literature review using scientific database and collate my information using information technology tools like excel spreadsheet. - I have the ability to communicate appropriately within an academic context, yet I would like to continue to develop my academic literacy abilities within wider contexts. - Since I have a planned secondment to Germany during my research project, I would like to learn German language and improve my proficiency.	- Attended the OR61 conference to gain more knowledge about operational research methodologies and sustainability dimensions in supply chain management. - Attended Python programming course in October 2019. - Attend the speaking skills for research purposes courses to improve my speaking ability for presenting my research in conferences (i.e. China) from October 2019. - Attend the academic writing courses form October 2019. - Attend German language course in winter 2019. - Independent study about network design, network optimisation, multi-objective optimisation. - Checking NATCOR initiative courses. - Attending some training on Multiple Objective Mixed Integer Programming (MOMIP) - Start to become familiar with PolySCIP software (equivalent of Cplex)
Cognitive abilities (A2) Including: - Analysing - Synthesising knowledge - Critical thinking	- I have well developed my analytical abilities during my master's level. - I can readily see the connections between my own research and previous studies and am able to synthesise new and previous information critically.	- Attend big data analytic classes - Attend courses relevant to how to be a creative critical thinker - Attending network events from the ReTrace project

	- I wish to further develop my independent and critical thinking skills.	
Creativity (A3) Including: - Intellectual insight - Innovation - Argument Construction	- I try to create ideas by investigating a wide range of related articles regarding designing of a CLSC supply chain and tend to develop my own understanding of intellectual position. - I understand the role of innovation and creativity in my research area. - I would like to improve my argument construction ability to be able to defend my research outcomes rigorously.	- Participate in intra-wp1 meetings regularly and actively seeking to collaborate with other ESRs in order to identify new and innovative ideas. - Participate in confirmation review sessions of the previous PhD students to get some ideas to develop my argument construction skills and understand how to produce convincing arguments to defend research theses.
RDF Domain B: Personal Effectiveness the personal qualities and approach to be an effective researcher		
	Reflection on your current ability/experience in this area and main priorities for the coming year	**Action to be taken to develop this area (if appropriate), agreed with your supervisor(s).**
Personal qualities (B1) Including: - Resilience - Self-confidence - Integrity - Self-reflection	- I believe resiliency is one of my best features. I had an experience in my master's thesis, that we (my supervisors and I) decided to change the entire project because of lacking of the required data and start from scratch with quite a different topic. - I am aware that I am a self-confident person but I'm not satisfied when it comes to demonstrating it. I'm willing to work on this skill to initiate challenges and engage with others. - I understand the standards of good research practice in SUMS and have completed the ethics approval; However, I need to work on some minor changes in order to get the final approval.	- Presenting my research work in cleaner production conference in china in November 2019. This will help me not only improve my self-confidence skill but also get some feedback to develop my strengths and improve my weak areas. - Attending the Research Integrity course (Mandatory).

	- As we have a diary file which we have to update our weekly progress in ReTraCE project folder, I try to dedicate a time to reflect on my practices and endeavour to recognize my strength and weaknesses and learn from my mistakes.	
Self-management (B2) Including: - Time management - Responsiveness to change - Work-life balance	- I am able to manage my time effectively by outlining a daily schedule for my works. - As I mentioned before, I'm a very resilient person and can adapt myself to any required changes easily. - The most important part of self-management is related to work-life balance which I think sometimes I forget to pay enough attention to it. Therefore, I need to use advisory resources to avoid pressure and relieve stress as well as enhancing my well-being.	- Updating the ReTraCE diary weekly. - Enrol in the gym exercises to improve my well-being. - Attend the ReTraCE Team retreat for ESRs in Naples in December 2019.
Professional and career development (B3) Including: - Career management - Networking - Reputation and esteem	- I have created my profile in social media (i.e: LinkedIn, ResearchGate, Academia) in order to present my own skills and experiences through effective CVs. - I have established a good relationship with my supervisors and colleagues. Moreover, I have engaged on social media with different groups which their members are working on circular economy principals; nevertheless, I need to enhance my participation in online networking. - I believe I have to work on my reputation and esteem in my own research area.	- Attend a lecture about Social Networking at the ReTraCE Team retreat in Naples in December 2019. - Take advantage of attending the conferences to develop my networking as well as gain reputation and esteem in closed-loop supply chain area. - Attend and interact with the ReTrace Partners (the University of Kassel, Högskolan Dalarna, PROTEG Spa, European Recycling Platform) regarding my secondment plans.
RDF Domain C: Research Governance and Organisation		

the knowledge of the standards, requirements and professionalism to do research		
	Reflection on your current ability/experience in this area and main priorities for the coming year	**Action to be taken to develop this area (if appropriate), agreed with your supervisor(s).**
Professional conduct (C1) Including: - Ethics - Respect and confidentiality - Attribution and co-authorship	- I have applied for the ethical conduct of research at the beginning of my career; however, I have to modify some parts of it to get approved. - Due to the type of data I will need for my research project, I do respect the right to confidentiality and anonymity of my colleagues and all other participants of ReTraCE project. However, I might need to gain more knowledge to manage this essential issue. - I understand the concept of attribution and co-authorship fairly enough, as I published an article in a well-known journal at my master's level.	- Modify the Ethical Approval as soon as possible. - Ask about institutional policies to avoid spreading the confidential data.
Research management (C2) Including: - Research strategy; - Project planning and delivery; - Risk management.	- I need to develop my understanding of how to align my own research with the research strategy at SUMS in supply chain management area. - I think I am able to set my research goals and assign a suitable priority to my activities. I regularly act on decisions agreed with my supervisors after each supervisory meeting and deliver weekly results. - I have completed the risk assessment procedure at SUMS.	- Present my deliverables according to the dedicated time at ReTraCE project's Gantt chart.
Finance, funding and resources (C3) Including - Income and funding;	- I understand the processes for funding and evaluation of research. - I understand the basic principles of financial management. Furthermore, the program	- Update my grant's spreadsheet monthly according to the spending on activities related to the ReTraCE project.

- Financial management.	coordinator (Mrs Patrizia Baldi) explained me about the financial amount that can be assigned to conferences, training courses and any activities related to the ReTraCE project in order to develop my deeper financial awareness. Therefore, we have created an Excel spreadsheet, to be able to manage my own grant.	
RDF Domain D: Engagement, Influence and Impact the knowledge and skills to work with others and ensure the wider impact of research		
	Reflection on your current ability/experience in this area and main priorities for the coming year	**Action to be taken to develop this area (if appropriate), agreed with your supervisor(s).**
Working with others (D1) Including: - Team working; - People Management; - Influence and leadership.	- As I have had the experience of working with other people from different backgrounds, I understand my own behaviour and impact on others; Now I'm working with other ESRs and have monthly online meeting with my research fellows. At the end, I always appreciate their contribution. - I wish to learn how to develop my leadership skills in order to be able to engage in debates with those who use the outputs of my research to achieve influence and impact.	- Attend workshop related to influence and leadership skills (if available).
Communication and dissemination (D2) Including: - Communication Methods; - Publication. - Technical Report Writing	- I actively engage in knowledge exchange and debate with my colleagues. - I have published a scientific article during my master's level; thus, I am familiar with the process of publication and academic exploitation of research results. In addition, I tend to produce	- Attend Speaking Skills for research purposes weekly to develop my communication abilities. - Preparing some materials in electronic format to publish in related journals.

- Policy Briefs - Press Releases	some publishable material during my PhD as well.	
Engagement and impact (D3) Including: - Teaching; - Public Engagement; - Global Citizenship.	- I wish to develop my knowledge about teaching at undergraduate level. - I understand the impact of my research on global citizens (at the national and international level).	- Attend the Introduction to Teaching at the School organized by SUMS.

Feedback (to be completed after the supervision in which the TNA is discussed)	
Comments from supervisor(s)	**Any further action agreed by the supervisor and the student [please specify]:**

Signature of researcher:	**Date: 01/01/2020**
Signatures of supervisor(s): Prof. Andrea Genovese	**Date:04/02/2020**
Signature of departmental PGR Director:	**Date:**