Economic Feasibility Analysis of a Medical Mask Closed-Loop Supply Chain: A Case Study in the Montreal Region

By

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Analyse de la viabilité économique d'une chaîne d'approvisionnement en boucle fermée de masques médicaux : une étude de cas dans la région de Montréal

Erika VILLALOBOS CORTES

RÉSUMÉ

Le monde a été confronté à une crise sanitaire mondiale due au covid-19. Cette situation a engendré une augmentation sans précédent de l'utilisation de matériaux médicaux à usage unique, notamment les masques médicaux. Cette étude se concentre sur la conception et la planification d'une chaîne d'approvisionnement (CA) en boucle fermée pour gérer la fin de vie des masques médicaux. Un modèle d'optimisation pour collecter et recycler efficacement les masques médicaux usagés est proposé. Les principaux avantages sont l'élimination correcte des produits contaminés et le recyclage des composants. Le réseau de la CA envisagé comprend des fournisseurs de matières premières vierges, des centres de fabrication de masques, des entrepôts, des centres de distribution, des clients institutionnels, des centres de collecte et de recyclage, et enfin, des clients pour les composants recyclés. Les décisions à prendre incluent les flux de matériaux dans le réseau, la sélection des fournisseurs et des centres de collecte et recyclage afin de maximiser le profit de la CA. Une étude de cas réaliste est créée sur la base de données réelles collectées auprès de différents partenaires industriels de la région de Montréal et environs. Divers scénarios sont analysés pour identifier les conditions dans lesquelles la CA est rentable

Mots-clés : matériaux médicaux à usage unique, couvre-visage, logistique inverse, chaîne d'approvisionnement en boucle fermée, recyclage, économie circulaire, rentabilité économique

Economic feasibility analysis of a medical mask closed-loop supply chain: a case study in the Montréal region

Erika VILLALOBOS CORTÉS

ABSTRACT

The world was exposed to a global health crisis due to covid-19. This situation generated an unprecedented increase in the use of single-use medical materials, notably medical face masks. This study focuses on the design and planning of a closed-loop supply chain (SC) for dealing with end-of-life medical face masks. An optimization model to efficiently collect and recycle used medical face masks is proposed. The main benefits are the correct disposal of contaminated products and component recycling. The considered SC network includes suppliers of virgin raw materials, medical face mask manufacturing centers, warehouses, distribution centers, business clients, collection and recycling centers, and finally, clients for the recycled components. Decisions to be made include material flows in the network, supplier (collection and recycling centers) selection in order to maximize the profit of the SC. A realistic case study is created based on real data gathered from different industrial partners in the Montreal region and surrounding areas. Various scenarios are analyzed to identify the conditions under which the SC is profitable.

Keywords: single-use medical materials, medical face mask, reverse logistics, closed-loop supply chain, recycling, circular economy, economic profitability.

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LIST OF ABREVIATIONS

CE	Circular Economy
CLSC	Closed loop supply chain
EOS	Economies of Scales
GHG	Greenhouse gas emissions
ILP	Integer linear programming model
MILP	Mixed Integer linear programming
OLSC	Open loop supply chain
PPE	Personal Protective Equipment
RFID	Radio Frequency Identification
RL	Reverse Logistics
RLN	Reverse Logistics Network
ROI	Return on Investment
SC	Supply Chain
WHO	World Health Organization

INTRODUCTION

In recent years, there has been a global concern about the scarcity of resources, the generation of waste, and the environmental effect of human activities. This is because for many years, linear economic models were the approach used for comprehending and handling economic systems as shown in figure 1. The main emphasis in these models is on production and consumption; "take-make-use-dispose", neglecting the consequences for natural resources and the environment (Andrews, 2015). However, as society's awareness regarding the finite nature of resources, waste generation, the disposal of valuable materials in landfills or incinerators, and the adverse consequences of uncontrolled expansion of end of life products considered as waste, it became evident that linear economic models have significant deficiencies. This wasteful practice, with its emphasis on constant consumption and disposal, depletes the land space and releases greenhouse gas (GHG) emissions, among others.

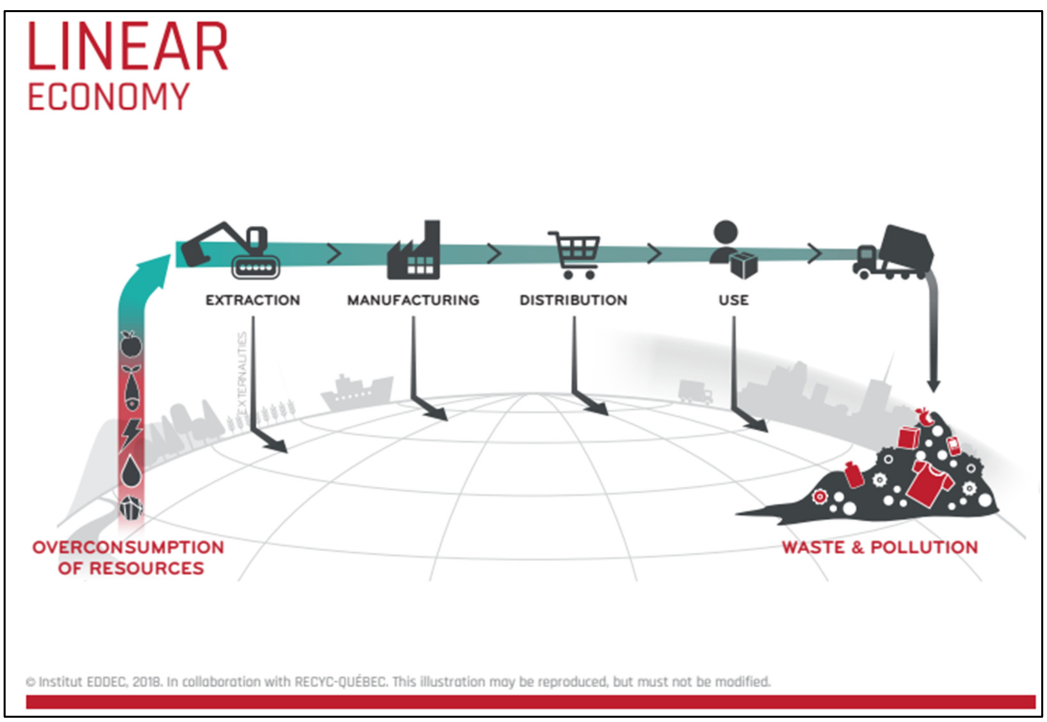


Figure 1 Representation of the linear economy of products
Taken from RECYC-QUÉBEC (2019)

In response to this issue, a new solution has emerged; the circular economy model (CE). With the CE model, the primary goal is to extend the lifespan of materials and products, thus reducing waste and optimizing resource utilization in every stage of a product or service's life cycle. It also contributes to the overall well-being of individuals, communities, and the environment (Morseletto, 2023).

CE aims to minimize waste and maximize the use of resources through two main mechanisms, as illustrated in figure 2.

1) Rethink: manufacture and consume more consciously products to use fewer resources and protect the environment.
2) Optimize: find innovative ways to extend the life of products that have already been used, or give them a new one, considering waste as a resource instead of a cost (RECYC-QUÉBEC, 2019).

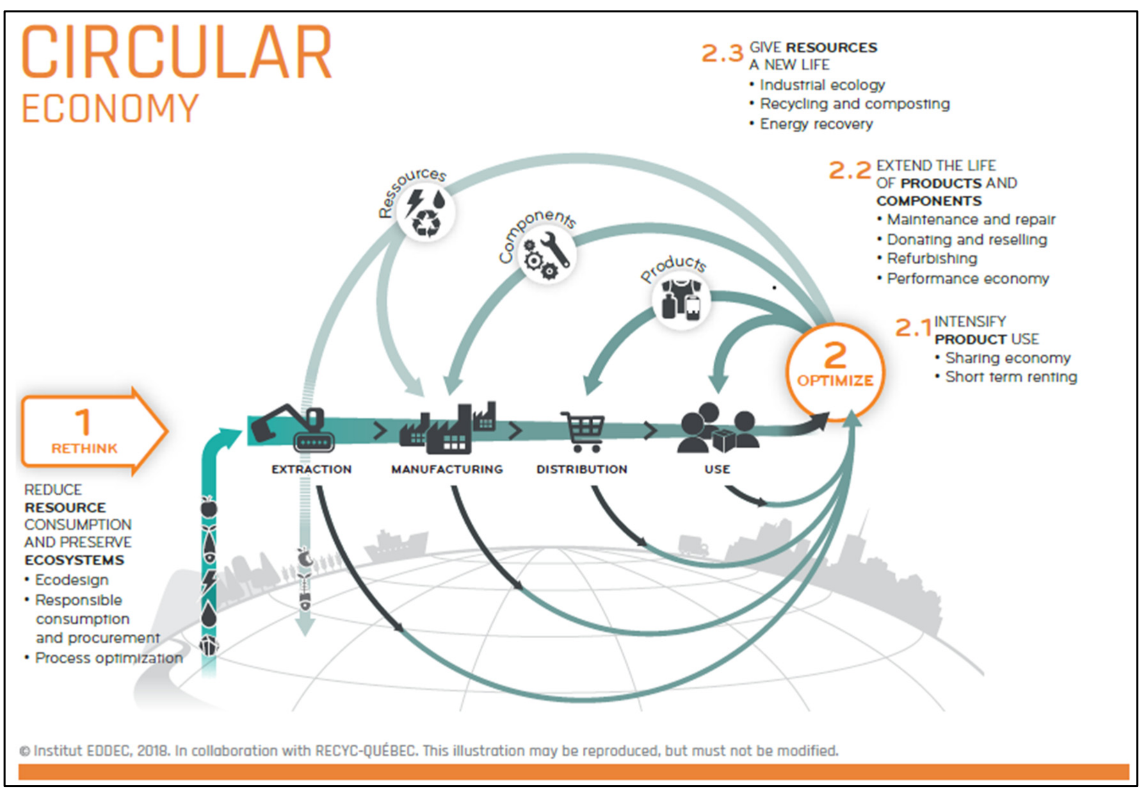


Figure 2 Representation of the circular economy model
Taken from RECYC-QUÉBEC (2019)

This circular model invites us to think of new ways of addressing current problems and propose or transform SCs in order to consider the possibility of a more sustainable way of using a product at its end of life. One of these problems was most notable during the covid-19 pandemic, where we witnessed the accelerated use of medical face masks and acknowedged the need to design and better plan the logistics of end of life medical face masks, which we address in this study.

The remainder of this thesis is organized as follows. Chapter 1 explains the motivation behind this work, its objectives as well as the research methodology adopted. Chapter 2 presents a review of the literature on existing optimization models that tackled the problem of reverse logistic (RL) and closed loop supply chain (CLSC) design and planning in the healthcare sector. Chapter 3 presents the problem description, our assumptions, and defines the notation and the formulation of a Mixed Integer Linear Programming Model (MILP). Chapter 4 presents a realistic case study that we used to solve and test our model the results, sensitivity analysys and a discussion. Various scenarios are analyzed to identify the conditions under which the SC is profitable. A conclusion regarding our contribution and the limitations of our study as well as directions for future research will be provided at the end of this document.

CHAPTER 1

RESEARCH PROBLEM

In this chapter, we present in more details the research context and motivation of this study, the research problem, the research questions, the objectives and finally the research methodology adopted.

1.1 Research context and motivation

The CE model widely benefits all industrial sectors. One example is the healthcare sector which can benefit from the recovery of personal protective equipment (PPE) such as medical face masks. The coronavirus outbreak caused a global health crisis from 2020 to 2022 because of SARS-CoV-2, also know as Covid-19. On January 30th of 2020, the World Health Organization (WHO) declared the outbreak as a public health emergency of international concern and a pandemic on March 11th (Sohrabi et al., 2020).

The coronavirus outbreak spread rapidly throughout the world. In the province of Quebec (Canada), the Prime Minister cited the Public Health Act and stated a public health emergency on March 13th of 2020. A few months later, this situation generated an unprecedent increase in single-use medical materials, notably in the healthcare sector. All Canadian provinces implemented sanitary measures to combat the coronavirus including wearing PPE such as medical face masks in the daily life for all inhabitants. Moreover, an emergency legislation on March 20th of 2020 was signed between the government of Canada and the private sector to guarantee some PPE manufacturing and supply during the pandemic. Among these agreements was the production of 157 million medical face masks by all Canadian medical face mask manufacturing companies. The goal was to lower the risk of infection by the SARS-CoV-2 virus (Prather et al., 2020; Spitzer, 2020). This resulted in an accelerated increase of using medical face masks and, therefore, as a global effect, a part of the used medical face masks ended upon coasts or beaches and water environments as a waste (Ardusso et al., 2021a; Xu & Ren, 2021).

The quantity of medical face masks used worldwide was approximately 129 billion monthly in 2021 (Oginni, 2022). Assuming that each medical face mask weighs 3.5 grams, this equates to 451,500 tons of waste per month generated around the world that year alone (Occasi et al., 2022). In addition, many sectors were using this PPE even before the pandemic, such as the healthcare, food, veterinary, electronic, chemical, and mining sectors. These sectors still use them after the pandemic. This confirms the emergency to implement adequate strategies for recovering these products at the end of their useful life. It can be a risk for humans and the environment if the generated waste is not handled properly (Sarkodie & Owusu, 2021). However, medical face masks were not recycled before the pandemic due to their regulated disposal through a specialized waste process, particularly in the medical sector (Rewar et al., 2015). Furthermore, medical face masks were initially created for single use, making recycling a relatively unexplored topic until the pandemic.

The medical face mask SC presents an interesting opportunity to explore how some aspects of the CE can be implemented while ensuring economic profitability and viability. As a matter of fact, there is a need to develop strategies to efficiently collect medical face masks at the end of their life. This will not only improve public health but also build a path to a more sustainable future that will extend beyond the pandemic.

The main objective of this work is to explore if it is possible to find an effective solution for medical face mask collection and recycling at the end of their useful life in order to manufacture and consume more consciously these products by extending their lifetime through recycling (i.e., bringing the recycled components back to the market) in the most efficient way. This problem can be addressed from the logistics optimization perspective by establishing a RLN integrated or not with the forward logistics network (a CLSC or an open loop supply chain - OLSC) and determining most efficient “paths” for end-of-life products collection and recycling to favor value creation from what would otherwise be considered as a contaminated pollutant. This is an example of how CE could be implemented in practice (Korhonen et al., 2018; Liu & Ramakrishna, 2021; Prieto-Sandoval et al., 2018).

1.2 Problem, objectives, and research questions

Traditionally, the SC includes only forward logistics (or forward SC) that aims to gradually transform raw materials into manufactured products to satisfy customers demand (Fleischmann et al., 1997). The objective is to ensure timely delivery of products in the correct condition and quantity to the customers. Transportation, distribution, warehousing, order fulfillment, and inventory management are examples of forward logistics operations

On the other hand, RL deals with the management of the reverse flows. It is referred to the management and ways of returning the end-of-life product flows in a SC (Agrawal et al., 2015). The main objective is to maximize the value of the products at the end of their useful life. The integration of forward and RL results in CLSCs (Kumar & Kumar, 2013) as illustrated in figure 1.1.When the RLN is integrated with the forward logistics network, it results in a CLSC or an OLSC. In OLSCs; end-of-life products are not collected by the original manufacturer but by an independent manufacturer (Doctori-Blass & Geyer, 2009). In a CLSC; end-of-life products are collected by the original manufacturer or by another company playing a role in the manufacturer's SC (Chouinard, 2003).

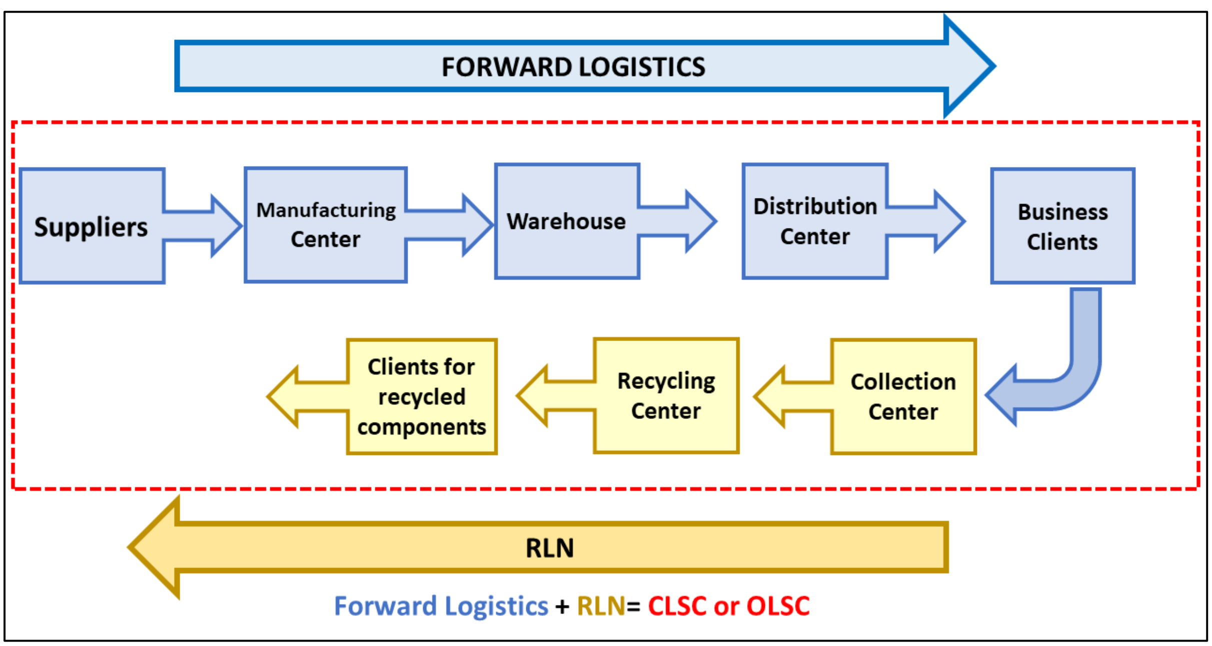


Figure 1.1 Schematic representation of a CLSC

The main objective of this thesis is to provide a decision-support tool for decision-makers to identify the best configuration of their RLN and CLSCs, by considering different parameters and constraints. In addition, it seeks to obtain the greatest possible profit and evaluate different scenarios to analyze which one brings the best return on investment. Therefore, this work contributes to address the important problem of efficient collection and recycling of medical face masks in a RLN or CLSC and validates its economic feasibility and viability.

We seek to address the following research questions:

- Q1: How can we design and optimize a CLSC or RLN for dealing with end-of-life medical face masks?
- Q2: What is the quantity of medical face masks that should be collected and recycled to obtain a desired ROI?
- Q3: What are the conditions that lead to an economically feasible medical face mask CLSC or RLN?

1.3 Methodology

In order to answer our research questions and achieve our objectives, this research is based on the following methodology, (a summary of the research methodology can be found in Figure 1.2) which encompasses four steps:

1) **Definition of the problem**:

   Two different approaches are used: A) Analysing current studies on responsible management of waste and products. In addition, analysing articles that include financial aspects such as investments and economies of scale (EOS) to identify existing gaps. B) Understanding the current situation and challenges in the industry of medical face masks (Canadian context).

A) Literature review analysis:

We conducted our literature review by considering papers that address CLSCs, OLSCs and RLN and how they approach end-of-life product management. We identified the related problems and the proposed methods for addressing them, particularly in articles that presented optimization models such as MILP models. We also identified the type of products studied in these papers (e.g., infectious medical waste, tissue waste, domestical and medical waste, pharmaceutical waste products, etc.) in the healthcare sector and their particularities such as planning levels, performance objectives and how these aspects were considered by the authors. In addition, we analyzed how the models proposed are formulated, what are the decision variables, and the limitations of these studies. The aim was to identify the gaps that exist in the literature.

B) Current situation and challenges in the industry of medical face masks:

In this step, through multiple interviews, we discussed with the quality manager of a Canadian company manufacturing medical face masks in the Montreal region to understand the current state of this industry and identify the most critical logistics and manufacturing challenges faced by manufacturers.

2) Mathematical model development

The second step consists in identifying the characteristics and assumptions of the problem to be studied with the help of the literature review and the information gathered regarding the medical face mask industry. This mathematical model is formulated as a MILP with the aim of determining the most profitable configuration of the CLSC or a RLN while considering multiple scenarios.

3) Data collection and case study:

The third step allowed us to obtain realistic data to build our case study. It is a joint effort of four collaborators including a medical face mask manufacturer, a logistics service provider, a recycling company, and a business client represented by an educational institution.

The major challenge lays in consolidating all the data to ensure its consistency as these partners operate independently without shared any networks or facilities with each other.

4) **Analysis of the results and discussion:**

   The fourth step is the mathematical model implementation in a Solver. We used IBM ILOG CPLEX. Version 20.1. Upon completion, an analysis of the obtained results was conducted. In this analysis, we explored different scenarios related to the quantity of used medical face masks returned to the collection center and the amount of investment required. Our objective is to identify the scenario that generates the most significant ROI over the years and identify the conditions of economic profitability.

5) **Analysis including EOS:**

   This last step involves developing a mathematical function that includes fixed and variable investments, while considering EOS. The objective is to determine the amount of medical face masks to collect and recycle to obtain a desired ROI (research question 2).

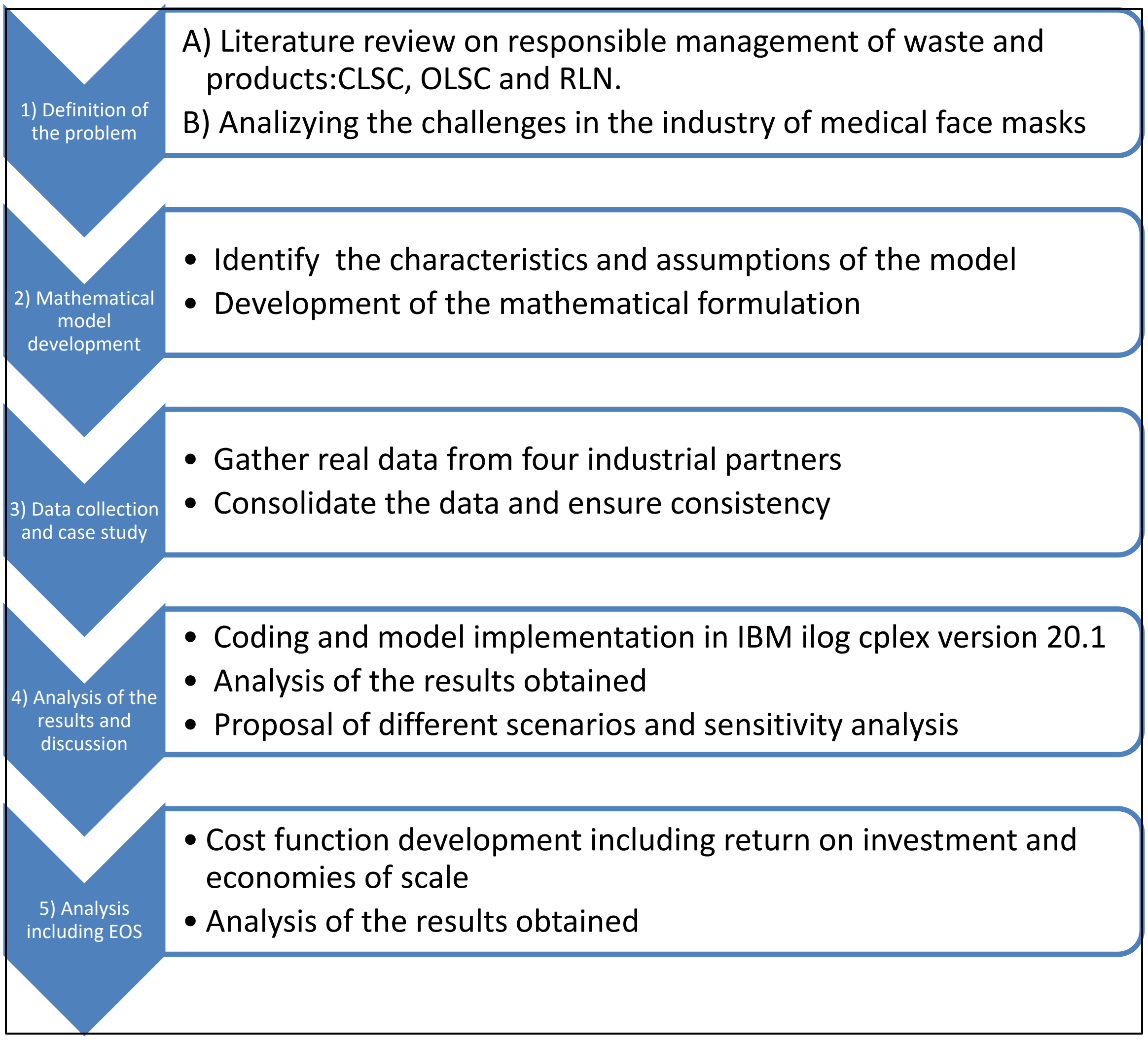


Figure 1.2 Research methodology

CHAPTER 2

LITERATURE REVIEW

This literature review provides a critical analysis of research works that have shaped the current knowledge within CLSC, OLSC and RLN in healthcare sector. This literature review is organized into six sub-sections, each dedicated to a specific aspect or theme relevant to this research project. Subsection 2.1 presents the potential risks of polypropylene, mainly when used in medical face masks, the philosophy of waste management hierarchy, and the best practices for managing polypropylene waste. Next, subsection 2.2 is carried out to obtain a complete understanding of the components used in manufacturing the medical face masks and the methods used in their production process. Subsection 2.3 gives a comprehensive understanding of the recycling process for medical face masks, its advantages, disadvantages, and environmental impacts, as well as existing disinfection processes with advantages and weaknesses. In subsection 2.4 we can learn about CLSC models published in the literature. Subsection 2.5 concerns OLSC and RLN models. Finally in subsection 2.6 we will analyze papers that consider investments or EOS in their models. This latter examination aims to explore the various approaches, outcomes, and conclusions in the literature. Note that in sub-section 2.6, we extended our review to encompass other sectors than healthcare because in our study we consider investments and economic feasibility.

2.1 Polypropylene waste as a potential risk

The presence of polypropylene waste in natural environments represents a substantial ecological risk (Ardusso et al., 2021b; Haddad et al., 2021). Indeed, medical face masks made of polypropylene have been identified as a significant environmental danger. Biological degradation does not affect polypropylene easily, as it is resistant to this type of degradation and can last 450 years without disintegrating (Ma et al., 2021). In addition, medical face masks can end up in bodies of water, contaminate them, and potentially enter our food, which would affect us even after the pandemic (Mavrokefalidis, 2020).

In order to prevent medical face masks from ending up incinerated or in a landfill, as was the case in Italy at the beginning of 2020 (*ISPRA*, 2020), the best practices for polypropylene waste management will be studied in this section of the literature review. The intention is to analyze solutions to reduce the adverse effects on the environment, reduce the waste and to follow the polices of CE. As a basis, we will use the fundamental philosophy of waste management hierarchy that establishes the levels to follow to think about the product cycle based on sustainability: minimization, recycling, resource recovery and engineering treatment. Figure 2.1 explains the hierarchy of polypropylene waste management (Appolloni et al., 2021; Steinhorst & Beyerl, 2021).

We can observe as a first option waste minimization that includes PPE best practices for their use and the use of reusable PPE if possible. These good practices comprise giving the equipment appropriate use, for example, using it every time the user needs it, for the time allowed, and in the correct position, and actions to avoid (see as an example figure 2.2 (Government of Canada, 2022). Once the first echelon has been completed, following the hierarchy is recycling, which we will address in the following paragraphs and as a last option we have the disposal that includes: landfill and incineration which is intended to be used if only if none of the above can be fulfilled.

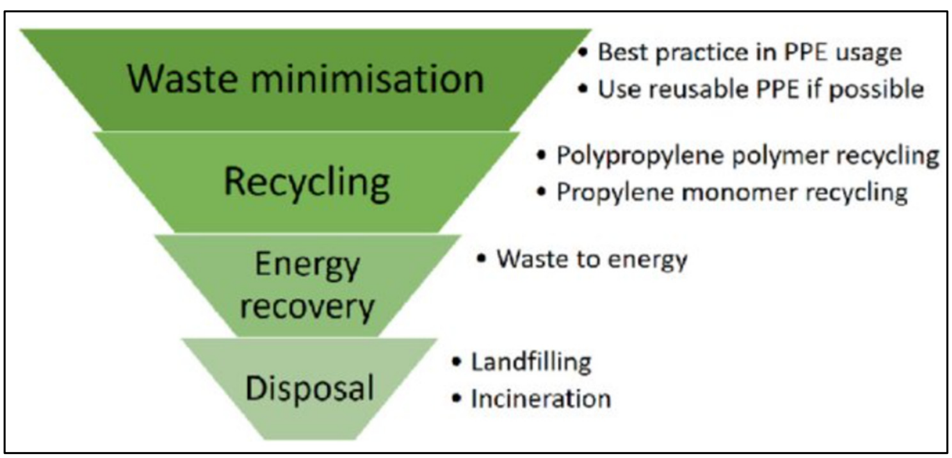


Figure 2.1 Polypropylene waste management hierarchy

Taken from Nghiem et al (2021)

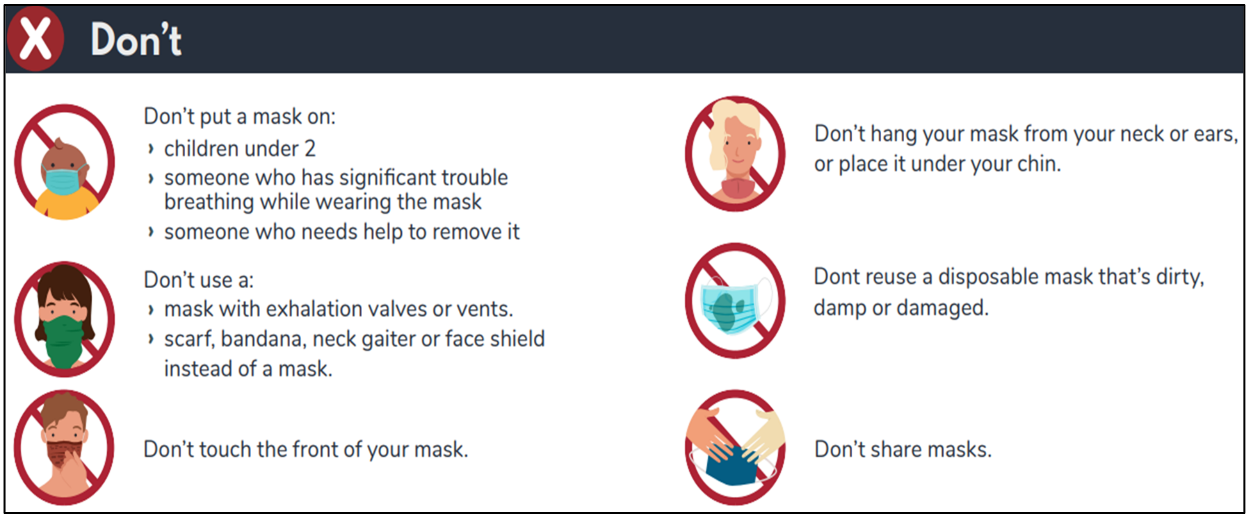


Figure 2.2 What to avoid in the use of medical face masks
Taken from Government of Canada (2022)

In the province of Québec, recycling medical face masks is an initiative of various companies already in charge of recycling certain products such as plastic, cardboard, coffee, laboratory waste. These companies proposed recycling medical face masks as an additional service. Among these companies are "Go Zero, Multirecycle, JWG, Teracycle, and Sanexen (RECYC-QUÉBEC, 2021). This initiative emerged since the health emergency forced the population to use medical face masks in large quantities, added to the high production rate of medical face masks to satisfy the demand. Recycling stands as the most embraced approach to plastic waste management and constitutes a crucial element of sustainable waste management practices. That is why an analysis of this process will be carried out and explained in Sub-section 2.3 (Bai & Sutanto, 2002).

2.2 Composition and manufacturing process of medical face mask

Medical face masks consist of premium thermoplastic materials like polypropylene (PP), polyethylene (PE), polyamide (PA), polyurethane (PU), polystyrene, and polycarbonate (Selvaranjan et al., 2021). Once they are gathered, decontaminated, and sorted, these materials hold the potential for recovery and resale within the recycling market. It was noted that polypropylene (PP) is a thermoplastic polymer which is the most frequently employed material in medical face masks, and possesses the potential for mechanical recycling, accounting for 78–91% of its weight as demonstrated by (Battegazzore et al., 2020). This could lead to an economic advantage in many circumstances, which will be assessed below. This mechanical recycling involves the physical reprocessing of the medical face masks collected to create new products other than the original (Ali et al., 2021; Crespo et al., 2021; Hou et al., 2021). Incorporating medical face mask waste as a secondary raw material for the creation of new products represents an additional move towards sustainability (Idrees et al., 2022).

Medical face masks are formed by three fabric layers, as shown in Figure 2.3. The outer layer comes from spun-bond non-woven polypropylene. It is a hydrophobic layer that protects the filtration of particles and water. The layer is made by spinning (or extruding) molten polymer into filaments delivered on a conveyor belt or rolling drum manifold, followed by hot bonding. The middle layer is made of melt-blown, non-woven polypropylene that is highly porous to allow for air passage while intercepting any water droplets that may be suspended in the air. This is manufactured by a melt-blown extrusion process. It is made through a process called melt-blown extrusion, in which molten polypropylene is blown from the die of an extruder onto a conveyor belt, often called a take-up screen. The inner layer is absorbent like the first layer and captures droplets from the user. It can also be made by filament spinning and thermal bonding. It involves a fusion blown process or spun-bond fabric. The melt-blown process is simple and is also used for the elastic trap of the medical face mask (Nghiem et al., 2021).

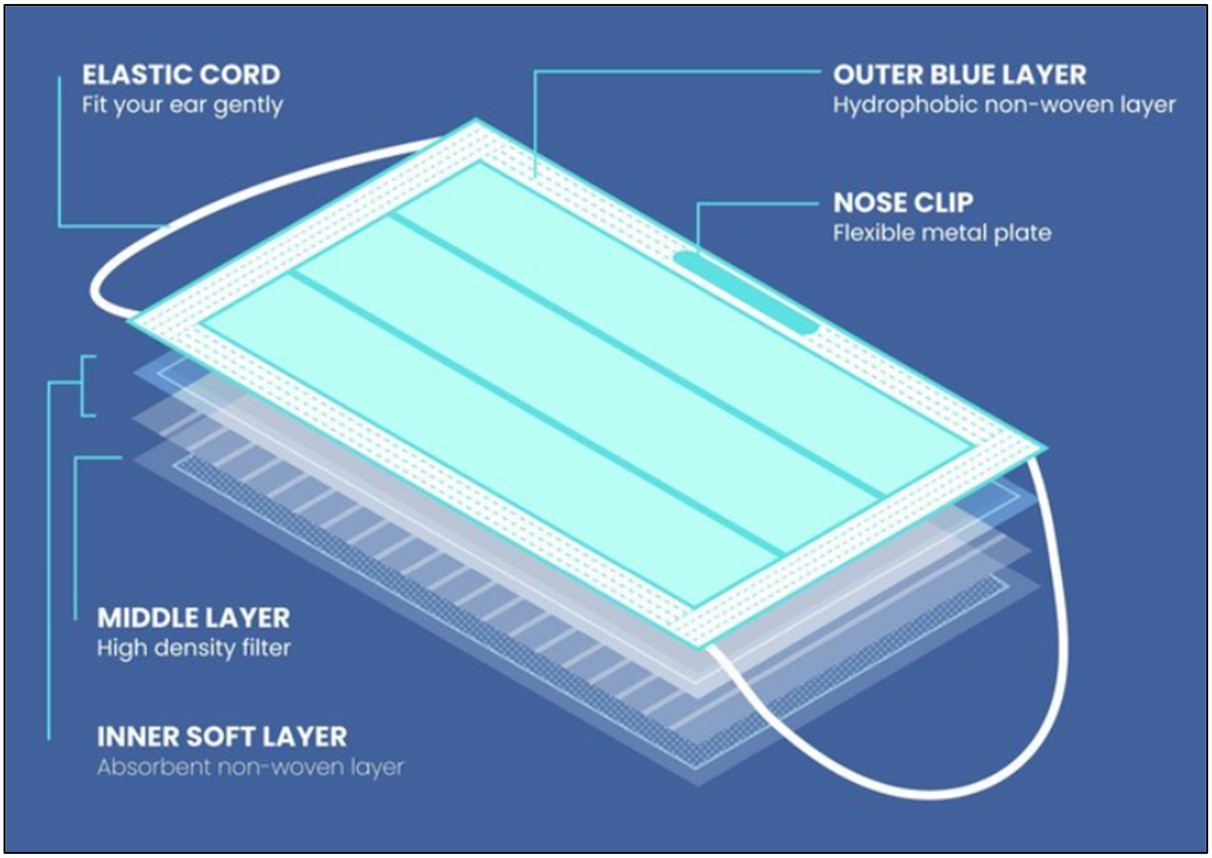


Figure 2.3 Three layers medical face mask "Image: Freepik.com (2023)"
This cover has been designed using assets from Freepik.com

These three layers are among the raw materials in our case study; the manufacturing process consists of assembling these layers in addition to aluminum nose bar and polyester ear loops to produce the medical face masks. All these components are illustrated in Figure 2.4. Note that the layers are delivered in three distinct large rolls to the manufacturing companies.

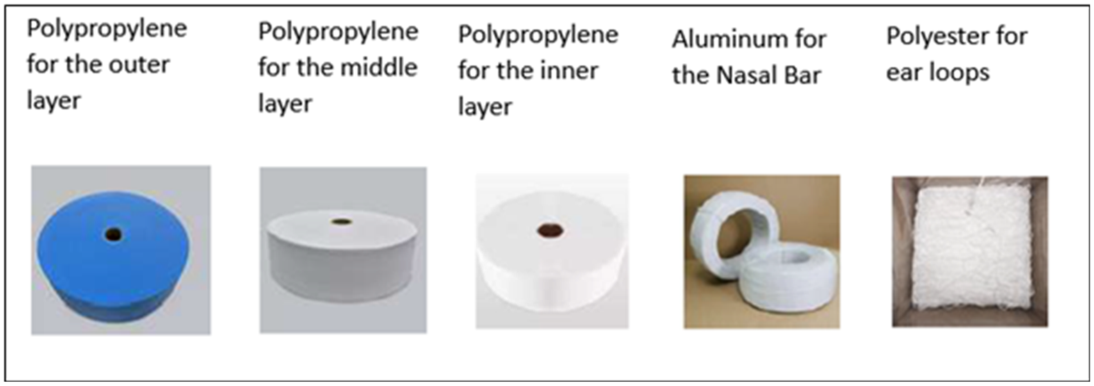


Figure 2.4 Illustration of materials required to make a medical face mask
Taken from Ménard et al., (2022)

The process begins by placing the rolls of raw material in the coil feeder of the machine. Then they are folded and pressed in the forming section, all three together, placing the filter in the middle of the inner and outer layer. Subsequently is added the aluminum nose band followed by cutting them to the predetermined size 17.5 * 9.5 cm (for adults). Finally it goes through automatic pressing adding the elastic bands for the ears (General Motors, 2021). This process can be seen in figure 2.5.

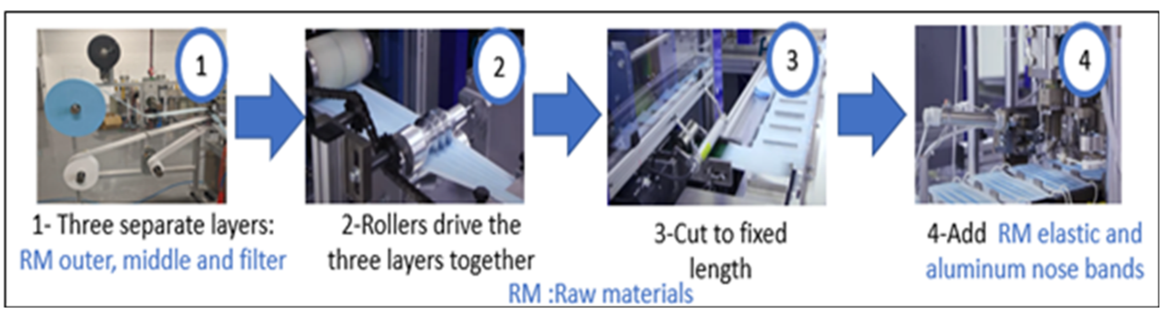


Figure 2.5 Manufacturing process of medical face mask
Adapted from PIA Automation, (2020)

2.3 Recycling process of medical face masks

As mentioned in section 2.1, polypropylene, which is the material with the highest proportion in a medical face mask, could cause environmental damage.

Integrating medical face mask recycling into waste management practices is a more sustainable, healthier, and environmentally friendly approach to the challenges posed by disposable medical face mask waste. There are various recycling technologies, such as mechanical, thermal, pyrolysis, and chemical reprocessing, which are described in Table 2.1. This table also presents their benefits, limitations, and environmental impact (Lyu et al., 2023).

Table 2.1 Types of recycling process for medical face masks, Adapted from Lyu et al. (2023)

Recycling technology	Advantages	Disadvantages	Environmental impacts
Mechanical reprocessing	• Relatively simple and cost-effective process to execute. • Can be applied to a wide range of products.	• The performance of recycled waste in relation to long-term performance is not well understood. • Potential for reduced material quality has limited the use and acceptance for different applications.	• Consumption of energy during procedures such as shredding and separation. • Production of waste byproducts (e.g., fibers or metal clips) and potential release of microplastics or other small particles into the environment.

Recycling technology	Advantages	Disadvantages	Environmental impacts
Thermochemical recycling	• Capable of processing various types of face masks and converting them into useful products. • Potential for energy recovery and can remove bacteria or viruses without the need for pretreatment.	• High-temperature processes require high energy input. • Equipment and infrastructural needs, such as extruders or 3D printers which allow easier blending	• Potential for greenhouse gas and air pollutant emissions, as well as other harmful substances, throughout the thermal process. • Generation of residual waste that may need to be disposed of properly.
Pyrolysis	•Toxins such as furans and dioxins are eliminated and can handle mixed materials and contaminants. • Can recover energy and produce valuable byproducts such as fuels, gas, and carbonaceous materials.	• High investment costs for the equipment and strict demand for the heat value of waste. • Operational challenges and technical issues need to be addressed.	• It has a low environmental impact. • Generation of residual waste (e.g., char or tar) that might require proper disposal.
Chemical repurposing	• Capable of converting medical face masks into alternative and value-added products. as road materials, plastic pallets, and storage containers • Do not change some structural characteristics of medical face masks.	• Requires specialized knowledge and equipment. • Limited scale, unable to reduce waste volume and mass.	• The potential for chemical waste generation during the conversion process. • The potential release of hazardous substances into the environment if not appropriately treated.

However, because the medical face masks at the end of its useful life contained contaminating particles, it was necessary to implement certain disinfection technologies, among which are: autoclave, dry heat, microwave/radio-wave, and ultraviolet disinfection, which are presented in the table 2.2 along with as their benefits and drawbacks.

Table 2.2 Disinfection technologies, taken from Lyu et al. (2023)

Disinfection technology	Key points	Advantages	Weaknesses
Autoclave Disinfection	•Temperature (121–134 °C) •Steam penetration •Types of containers •Chamber air removal	•High sterilization efficiency •Reliable, efficient, and simple •Low installation and maintenance costs	•Not suitable for pharmaceuticals, radioactive and pathological waste •Limitations in the treatment of large volumes waste •High energy input •Cannot reduce waste volume
Dry heat technique	•Temperature (121–134 °C) •Steam penetration •Types of containers •Chamber air removal	•High heat efficiency •Low costs and environmentally friendly	•Slow heat penetration •Not suitable for plastics
Microwave/ radio-wave Disinfection	•Temperature (177–540 °C) •Wavelength (1 mm–1 m) •Frequency (300–3000 MHz) •Reverse polymerization •Moisture content	•High efficiency, low pollution, and limited heat loss •Suitable for infectious and pathological waste	• High capital investment and high running costs •Need to adjust the humidity of the waste

Disinfection technology	Key points	Advantages	Weaknesses
Chemical Disinfection	•Chemicals •pH •Contact duration •Mechanical and chemical Mixing	•Widely accessible and easy •Lower costs	•Cannot reduce volume and mass of waste. •May cause skin irritation or respiratory sensitization
Ultraviolet (UV) Disinfection	•Wavelength (200-400 nm) •Exposure time	•Chemical-free •Environmentally friendly •Lower costs	•Low efficient •Require appropriate positioning and exposure time

In the case study which will be analyzed in Chapter 3, ultraviolet disinfection will be the base technologies used. This technology has proven its ability to kill or inactivate microorganisms at a low cost and chemically free (Tyler Irving, 2020).

The following subsections examine how authors in the literature addressed waste management concerns, end of product lifecycle, product reuse, recycling, and the CE as shown in table 2.3. Based on the classification, we take note of the criteria of the planning levels most studied in the literature, as well as the performances and types of SC studied, the applied cases, and the most commonly used indicators to integrate the ROI and EOS in the analysis of their results. Most of the studies are related to the SC of the healthcare sector, however in a second phase of research it was extended to other sectors such as the plastic industry, energy, electronics, automobiles, among others. The purpose behind this was to examine papers that also consider relevant information related to investment in their models. Further details will be explored in subsection 2.7.

2.4 CLSC models

Shi (2009) designed a CLSC for medical waste (sharp and tissue wastes). The medical waste can be sterilized, dismantled, remanufactured, or sent directly to disposal centers.

Products that complete their remanufacturing process without being sent to the disposal center are sent to facilities to be sold. This study addresses location-allocation decisions, i.e., when it is necessary to open a facility and which products quantities should be handled at each SC echelon.

Kumar & Rahman (2014) analyzed the obstacles and benefits of implementing RFID (Radio Frequency Identification) technology in a CLSC of the bedding department of a Singaporean hospital. The authors developed a discrete event simulation model with the aim of minimizing the cost of misplacing inventory in the bedding department. The authors showed that implementing RFID improved the performance of the CLSC. The performance is related to the operational efficiency of inventories by having greater traceability and visibility of bedding and cost reduction by avoiding the replacement of this bedding due to thefts. The saving was $140 US per day.

Nurjanni et al. (2017) studied a green CLSC comprising factories, warehouses, customers, and distribution centers with the objective of minimizing the total costs of the SC and carbon emissions. The decision variables are binary and continuous: the opening of facilities, the type of transportation between facilities, and the amount of product to be transported. The authors analyzed this model through a numerical example (because of not having a specific case with real data). The results demonstrate the capability of the model to handle trade-offs (allowing for the trade-offs between total costs and CO2 emissions) and identify optimal network designs. Three different scalarization approaches, including the weighted sum method, weighted Tchebycheff, and augmented weighted Tchebycheff are applied to solve the multi-objective optimization problem, analyze the sales and the limitations of this model. The application of mathematical models has not yet been completed and it is limited by model boundaries. The model is not suitable for solving green SC (GSC) problems in actual complex situations. Further work is needed to improve the model and explore its sensitivity to different scenarios and solving methods for multi-objective optimization.

Setiawan et al. (2021) proposed a CLSC model encompassing three objectives. The first one maximizes profit, by considering the quantity of medical face masks sold and recycled and the costs of purchasing raw materials, manufacturing, costs of activating/operating recycling and collection centers, and transportation cost. The second objective minimizes the carbon footprint of medical face mask transportation between the different centers of the SC. The third objective maximizes job creation at recycling and collection centers.

Tirkolaee et al. (2022) proposed a MILP model for optimizing a CLSC where three types of masks (N95, KN95, and surgical masks) are considered. It is a tri-objective model that seeks to minimize the SC costs, pollution by emissions due to transportation and operational processes, as well as the people infectious risk.

2.5 OLSC and RLN models

Budak & Ustundag (2017) proposed an Integer Linear Programming model (ILP) for the correct management and disposal of waste by clinics and hospitals. Their study includes a case study in Turkey. Medical and domestic waste is evaluated and can be treated by sterilization, burning centers, burying with lime, or grinding. The mathematical model seeks to minimize the total cost of the SC. Among the decisions considered are the storage and treatment centers to be activated, inventory levels, and the amount of waste allowed in each center.

Wang et al. (2019) proposed a dynamic approach combining an optimization model with a Gray Gm prediction model (Chen & Huang, 2013) to study the amount of healthcare waste in urban areas over a long duration (3 years).This healthcare waste includes waste containing viruses, hazardous materials or radioactive components. A case study from Shanghai hospitals was considered. The authors developed a bi-objective non-linear optimization model in which they seek to minimize the negative effects caused to the environment and the total cost of the SC. Negative environmental impact is measured by multiplying the distance between facilities and the waste inventory by an environmental impact factor. The decisions to be made are where to activate the collection, transit, and processing centers and the quantity of medical waste allowed in each of the facilities as well as transportation modes to use.

Ranjbar & Mirzazadeh (2019) developed a mathematical model to design a pharmaceutical OLSC for the disposable of used medicines. Their objective was to minimize the total cost of the SC (i.e., fixed opening costs of new facilities such as distribution, production and collection centers, costs of production, transportation, and operation of each of the parties involved in the SC).

(Kargar et al., 2020) proposed a robust possibilistic programming model for designing an OLSC under uncertainty for the secure disposal of medical wastes such as blood-soaked bandages, sharps, surgical waste, blood and body fluid, by considering different ways to select the best technology for waste treatment. The researchers consider four special treatments for waste disposal: incinerators, autoclaves, microwaves, and chemical materials, each one received a score from environmental experts. They developed a tri-objective optimization model applied to a case study in Iran (Babol city). Their first objective aimed to minimize the total cost of the SC (operating costs to enable new storage, treatment, and collection centers). The second maximizes the environmental score related to treatment selection. This objective also minimizes the damages to workers that would be caused by the selected treatments. Finally, the third objective seeks to leave the least amount of waste inventory in the storage centers. The decisions to be made include determining the location of transfer stations and treatment centers, technology selection and determining waste flows between medical and storage centers.

Alizadeh et al. (2020) designed an OLSC for the disposable of healthcare supplies such as dressing set, peripheral venous catheter, and latex gloves. The authors developed a bi-objective mathematical model based on the Bounded De Novo Programming approach. The first objective aims to maximize the profit. The revenues are generated by the sale of medical items to hospitals, sterilization services from clinics, and the sale of recycled waste to recycling facilities. The costs are related to the activation of collection centers, warehouses, sterilization centers, transportation, acquiring medical supplies, and expenses of the municipality for eliminating end-of-life products. The second objective aims to reduce the biological risk by minimizing the number of travels and trajectory from the clinics to the sterilization facilities. The case study's decisions (in Iran) concerned the activation of new facilities, the product amount to be transported, and the optimal number of trips.

Due to the health emergency caused by Covid-19, many researchers proposed models adapted to this new situation. This is the case of (Kargar et al., 2020) which is based on (Kargar et al., 2020) previously discussed. The authors developed a tri-objective mathematical model considering all possible sources of contamination of Covid-19. The main purpose is to help managing infectious medical waste resulting from diagnoses and medications of patients with Covid-19. The first objective minimizes the total cost related to collection, treatment, and burial operations. The second one minimizes the probability that unwanted events associated with the transport and treatment of virulent waste occur. The third objective minimizes uncollected waste.

Yu et al. (2020) proposed an OLSC mathematical model to support decision-making regarding the location of temporary facilities. The objective is to have enough space to handle the most significant volume of medical waste and avoid its accumulation over long periods, and to optimize the transportation plan. Although the model is focused on mitigating the probability of contracting Covid-19 through medical waste, it also seeks to minimize the costs of installing and providing service in the temporary facilities, such as transit centers. The model was tested on a case study in the city of Wuhan (China), where the spread of the virus was simulated using the SEIR (Susceptible-Exposed-Infected-Recovered) model. SEIR is used to analyze and predict the behavior of the spread of a disease (Li et al., 2001) .

Nosrati-Abarghooee et al. (2023) proposed a RLN for healthcare waste management considering epidemic disturbance under uncertainty. The SC is conformed by waste generation nodes, collection centers, treatment centers, recycling centers, and disposal centers. The decision variables include location of facilities, capacity levels of the collection centers treatment technologies selection, determination of the amount of waste to be treated as infectious, allocation of resources to minimize total costs and population risk

Govindan et al. (2022) proposed a RLN which includes hospitals, collection centres, treatment centres, recycling centers and disposal centres, transport routes and flows of medical waste within the network. The authors develop a strategic model related to various decisions such as facility location resource allocation, and transportation route design to ensure efficient and sustainable disposal of medical waste.

2.6 Models that address investments

Samuel et al. (2021) provides a literature review on quantitative studies related to decision-making in CLSC and integrating EOS, reliability/quality, and transshipment. The literature review shows that EOS play an important role in the design and planning of CLSCs. Research shows that the CLSC network with EOS generates higher profits compared to models without EOS. Overall, incorporating EOS considerations into CLSC design can improve profitability and operational efficiency. The authors also present a MILP model suitable for creating a multi-component (different pieces that make up a product), multi-product SC considering transshipment and EOS. Its objective function seeks to reduce the environmental impact and maximize the profit; this is achieved by minimizing waste and promoting the reuse of products. The revenues are obtained from selling new products and selling the remanufacturing used products. The costs encompass the opening of inspection, remanufacturing, and disassembly centers, the purchase prices of new products, inter-facility transportation costs, and costs associated with inspection, disassembly, and remanufacturing of used products. Finally, the concept of EOS was integrated into the selection of the capacities and dimensions of the inspection, remanufacturing, and disassembly centers, which, according to their sizes, affect the opening fixed cost. This is based on the quality and condition of the products or components being received. For example, if the returned products or parts exhibit high reliability, a reduced remanufacturing center capacity suffices, as there are more items available for refurbishment or parts recovery via disassembly. Conversely, in cases of low reliability (large quantity of damaged items), a larger remanufacturing centers capacity is necessary, achievable by either augmenting the number or size of those centers. All collected products are inspected, one percentage becomes remanufactured, while the other percentage arrives with high reliability, in which case , it is only disassembled. Dismantling, and remanufacturing centers are opened according to the quantity of products or used parts that arrive at these facilities. It is not specified in the numerical example used what type of products are studied, but it can be concluded that this is a theoretical model that could be applied to products in the automation or electronic sectors.

Santander et al. (2020) proposed a CLSC network design for recycling plastic obtained from 3D printing technologies. The authors developed a bi-objective MILP model to analyze its possible advantages and consequences in terms of economic and environmental sustainability. The model maximizes the sum of economic and environmental benefits. The economic benefits are generated by the savings from recycling 3D printing parts compared to buying virgin filaments as raw materials for the process. The authors consider increasing plastic waste collection, recycling, and optimizing transportation routes to maximize environmental benefits. The decision variables are to identify the most suitable locations for the recycling facilities, establish the optimal number of routes and the collection sequence, and select the transportation mode. To demonstrate the viability of the proposed optimization model for the plastic recycling network, the authors examined a French case study. The results show that there is a 69.5% decrease in carbon emissions compared to the scenario without recycling and a benefit of 317.8 euros per month. They concluded that this is not a global optimal solution, because the model was run with a 2-hour limit on GAMS CPLEX software, but it is possible to consider this tool as a reference for future projects. The authors study the EOS through a sensitivity analysis where the price of virgin plastic filaments is varied. As 3D printing expands, there is a larger quantity of 3D plastic waste, enhancing production manufacturing capacities for recycled plastic filament products. EOS is expected to reduce production costs. On the contrary, the market purchase price of virgin plastic filaments may undergo future changes, impacting the economic benefits when comparing prices between virgin and recycled filaments.

Pérez-Iribarren et al. (2023) explore the efficient configuration of a power generation SC within residential structures (hybrid thermal installation of heating and hot water). They propose a MILP model with the aim of minimizing the total costs comprising the annual fixed investment and the variable investment for installing equipment for generating energy such as biomass boilers, internal combustion engines, solar thermal collectors air water heat pump, photovoltaic modules and thermal energy storage and minimizing the carbon emissions. The annual fixed investment represents the budget for potentially installing those equipment depending on the demand(in kilowatts). The variable investment accounts for the maintenance cost of the technologies, calculated as a percentage of the initial investment corresponding to the size. This model aims to find an efficient way of designing and selecting technologies and their sizes. The decision variables are the installation or non-installation and selection of technologies such as boilers, heat pumps, internal combustion engines, the operation (or non-operation) of the internal combustion engine and whether the final heating temperature is high or low. To analyze the impact of this model, a case study in a cold area of northern Spain was used. The results show that the implementation costs were reduced by 15% and GHG emissions were reduced by 56%.

Fazlollahi et al (2012) developed a strategic decision-making tool to select the most attractive configuration, activities and processes to convert energy from one form to another like the creation of electrical power or the generation of heat. This tool is based on a MILP model=, which is capable of delivering an optimal solution. However, given the uncertainty of market conditions and available assets, it becomes essential to explore more than one combination. To address this, the Evolutionary Multi-Objective Optimization algorithm, in conjunction with Integer Cut Constraints (ICC), is employed. Its objective function seeks to minimize the total costs, which are the sum of annual operational and investment expenses, and the emissions of carbon. The decision variables are the maximum size of energy conversion technologies as well as the choice of fuel and utilization level of the selected equipment. The annual investment cost includes fixed cost for installing technologies, operational cost for the maintenance of this technologies and electricity price.

Azaron et al. (2008) present a stochastic Mixed Integer Nonlinear Programming model that seeks to minimize the financial risk of investing in constructing certain facilities and minimize the cost of the SC. This model focuses on a forward logistics network encompassing suppliers, manufacturing centers, warehouses, and customer centers. The decision variables involve investment choices in manufacturing centers or warehouses and the transportation of each product from suppliers to customers. A numerical experiment was carried out where the product is bottles of wine. Different scenarios were studied with different parameters related to uncertainty, demand, supply, processing, transportation, shortages and capacity expansion costs. In this study, it is verified whether the initial investment budget is exceeded or not. The results show that this approach leads to create medium-sized SC scenarios (around 10 facilities).

Boukherroub et al. (2017) proposed a generic model to identify the optimal conditions under which a wood pellet SC is profitable while taking into account EOS. The model identifies optimal feedstock locations, optimal supply quantities and establishes the optimal production capacity. The objective is to maximize the total profit, considering various factors such as market demand, wood pellet prices, feedstock supply capacity, procurement costs, transportation costs, and production costs. The model was applied in a real case study in eastern Canada. The authors calculated the ROI, based on the optimized profit and investment required for different production capacities. The ROI was used as an indicator for analyzing long-term profitability. The EOS was included when selecting the production cost for each of the production capacities. In Table 2.3, a summary of the papers investigated from subsection 2.4 to 2.6 is shown.

Table 2.3 Classification of literature review according to performances, planning levels, type of SC and economical criteria

Authors	Planning levels			Performances			Type of the SC			Experiment type					
	STRATEGIC	TACTICAL	OPERATIONAL	SOCIAL	ECONOMICAL	ENVIRONMENTAL	CL SC	OLSC	RLN	CASE STUDY	NUMERICAL EXAMPLE EXAMPLE	INVESTMENT	EOS	ROI	SECTOR
(Shi, 2009)		X			X		X				X				Healthcare
(A. Kumar & Rahman, 2014)		X			X		X			X					Healthcare
(Setiawan et al., 2021)		X		X	X	X	X				X				Healthcare
(Budak & Ustundag, 2017)		X			X			X		X					Healthcare
(Wang et al., 2019)		X			X	X		X		X					Healthcare
(Ranjbar & Mirzazadeh, 2019)		X			X			X			X				Healthcare
(Kargar, 2020)		X		X	X	X		X		X					Healthcare
(Yu et al., 2020)			X	X	X	X		X		X					Healthcare
(Pérez-Iribarren et al., 2023)		X		X	X	X	X			X		X			Healthcare
(Santander et al., 2020)					X	X	X			X		X			Plastic
(Alizadeh et al., 2020)		X			X	X		X		X					Healthcare
(Pérez-Iribarren et al., 2023)			X		X	X			X	X					Hydroelectric
(Samuel et al., 2021)	X				X	X	X				X			X	Automotive

Authors	Planning levels			Performances			Type of the SC			Experiment type		INV	EOS	ROI	
(Fazlollahi et al., 2012)	X				X	X		X		X		X			Energy
(Nurjanni et al., 2017)		X			X	X	X				X				Electronic
(Azaron et al., 2008)		X			X				X		X	X			Wine
(Nosrati-Abarghooee et al., 2023)		X			X	X			X		X				Healthcare
(Govindan et al., 2022)	X				X				X	X					Healthcare
(Balci et al., 2022)		X		X	X	X			X	X					Healthcare
(Boukherroub et al., 2017)		X			X		X			X		X	X	X	Bioenergy

In summary, there is a rich literature that addresses waste management at the three planning levels of the SC. However, we observe the absence of studies that analyze in combination the ROI and EOS in healthcare SCs (CLSC, OLSC and RLN). Finally, there are no articles reporting on Canadian case studies, which propose optimization models for recovering medical face masks at the end of their useful life. Our study contributes to address these two gaps. It proposes a MILP model solved by using a realistic case study in the Montreal region. It aims to determine the best medical face mask SC configuration (CLSC or RLN) ensuring economic profitability and feasibility. The model and the results are published in a Conference article (CIGI QUALITA MOSIM, 2023) (Villalobos et al., 2023), and presented (with some extensions) in the remaining chapters.

CHAPTER 3

MATHEMATICAL MODEL FORMULATION

In this chapter, we provide a detailed description of the problem examined in this study, along with the assumptions that guided the development of our mathematical model. We also introduce the mathematical model formulation (notation, parameters, decision variables, objective function and constraints) and explain our proposed model formulation

3.1 Problem description

Our study focuses on the design and planning of either a CLSC or an RLN. The CLSC considered generates its revenues from selling procedural medical face masks and recycled components (e.g., polypropylene) from used medical face masks. In other words, the medical face mask manufacturing company is the one responsible for collecting, recycling and selling the recycled materials (cases 1 to 4 described below). The SC network comprises suppliers of raw materials for manufacturing the medical face masks, manufacturing centers, warehouses, distribution centers, business clients (forward logistics network), collection centers, dismantling and recycling centers and clients for the recycled components. The RLN comprises only the business clients of the medical face mask, the collection centers, the dismantling, and recycling centers as well the potential clients for the recycled components (case 5). The recycling process consists in decontaminating, dismantling and separating the three components of the medical face mask; elastic, aluminum, and filters. The main component recycled is the filter since it is the component that is received in the most significant quantity and from which polypropylene can be produced. This synthetic fiber is highly sought after in the market to create plastic products. However, in some of our scenarios, we also consider the possibility to recycle the aluminum part.

The problem consists in determining the efficient strategy for the collection and recycling of medical face masks at the end of their useful life. The decision to be made are to determine the material flows through the network (the different echelons of the SC are shown in figure 3.1), and the optimal supplier selection. In addition, multiple SC configurations are studied, which will help us to decide where recycling and collection centers should be established to obtain the best profit. The problem could be presented from two different economic perspectives: minimizing the SC total cost or maximizing the total profit. We have addressed the problem with the profit maximization perspective because we are interested in studying the profitability and economic feasibility of the SC. Note that the SC design decisions are not directly included in the mathematical model formulation. They are considered in the different cases described in this chapter (cases 1 to 5) and analyzed in Chapter 4.

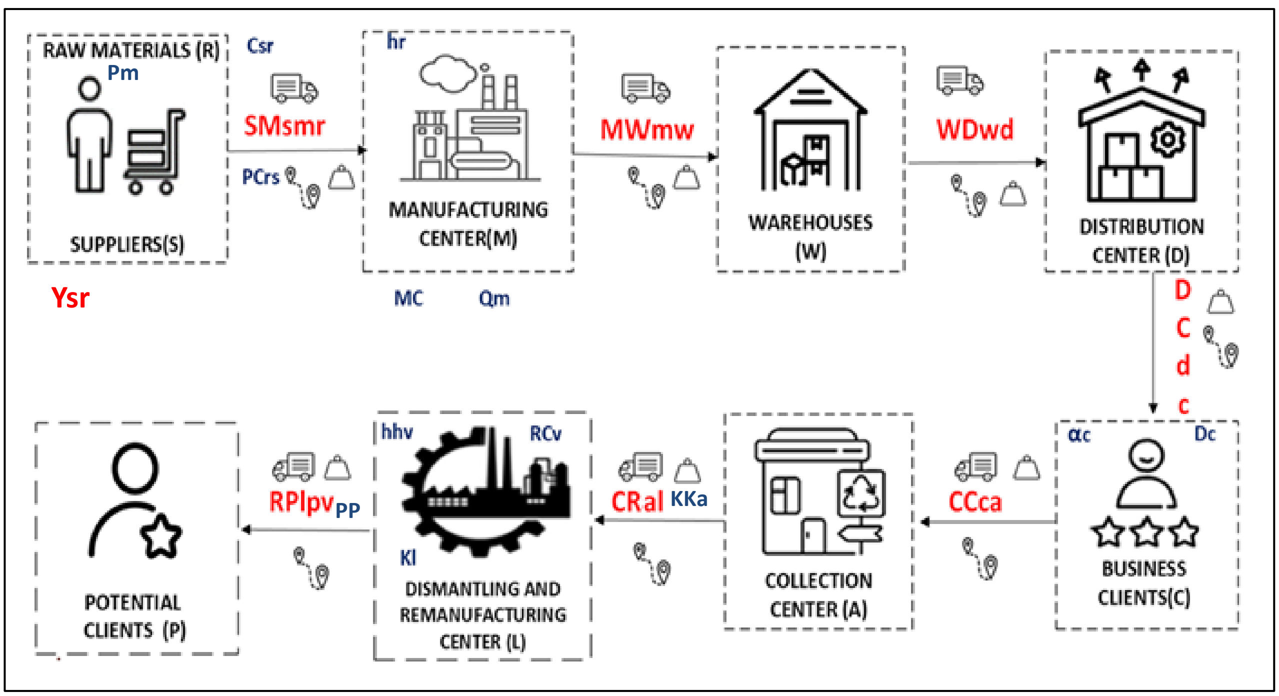
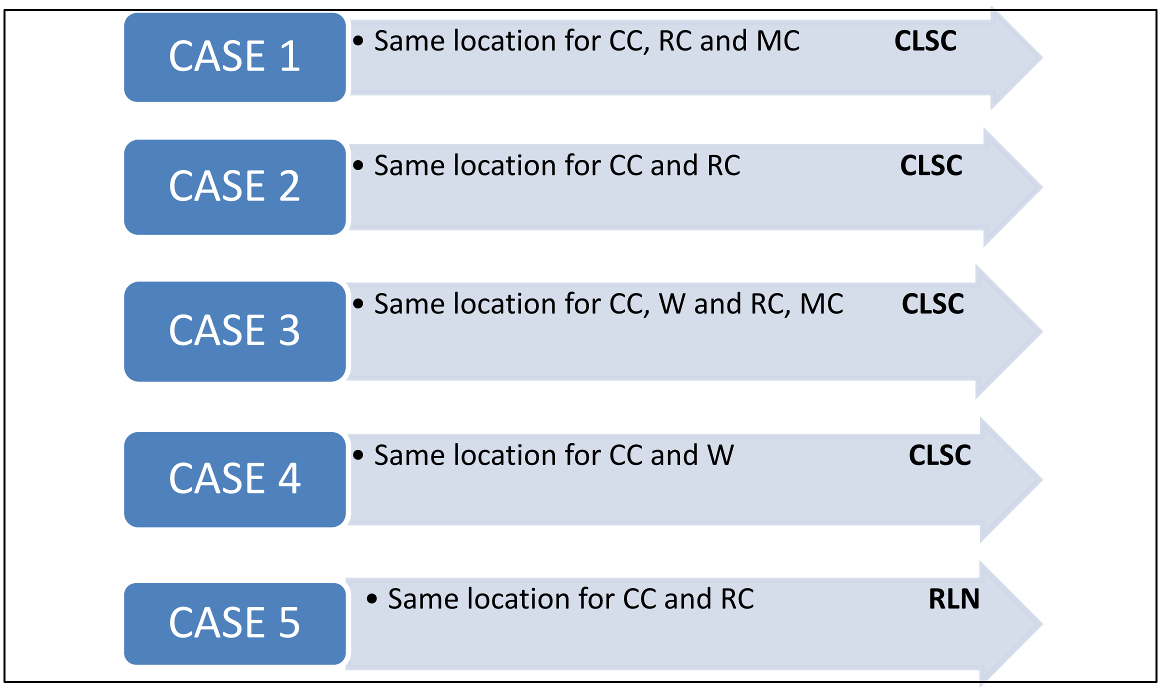


Figure 3.1 Medical face mask CLSC configuration and planning problem formulated as a MILP

To build a realistic case study, we collaborated with different companies in the Montreal region and in the province of Québec, involved in medical face mask manufacturing, raw material supply, medical face masks distribution, used medical face mask collection, medical face mask and polypropylene users (clients of medical face masks and polypropylene, respectively). The medical face mask manufacturer has established its manufacturing, warehouse, and distribution centers in Montreal Island. We are interested in studying different configurations (cases) of the used medical face mask RLNs such as a CLSC, where the manufacturing company carries out the collection and recycling process itself or a RLN under the responsibility of a distinct company that would operate independently or in collaboration with the manufacturing company. The creation of these cases aimed to offer decision-makers a range of potential SC configuration options (CLSCs or RLNs). By presenting different cases, each configuration can be analyzed individually, allowing for more thorough profitability analysis. To this end, we defined five different cases as shown in Figure 3.2. Each of these cases encompasses three scenarios, with a varying percentage of returned medical face masks by the clients; 80%, 50% and 25%. The purpose behind that is to analyze what would be the impact on the profitability and ROI depending on the amount of used medical face mask collected. We performed an additional analysis, in section 4.4 (ROI with economies of scale)to determine what is the right quantity of used medical face masks which should be collected and recycled to obtain a desired ROI while considering EOS.



CC: Collection center, W: Warehouse, RC: Recycling center, MC: Manufacturing center

Figure 3.2 Scheme of cases studied

The first four cases present CLSCs since the manufacturing company carries out the collection and recycling processes. In the first case, collection, recycling and manufacturing centers have all the same location as shown in figure 3.3. The investment, in this case, includes extending the (existing) manufacturing center with the necessary space area, technologies, machinery, and human resources to collect/store used medical face masks and produce/sell polypropylene pellets. Note that the investment taken into account covers both CLSC and RLN for all cases.

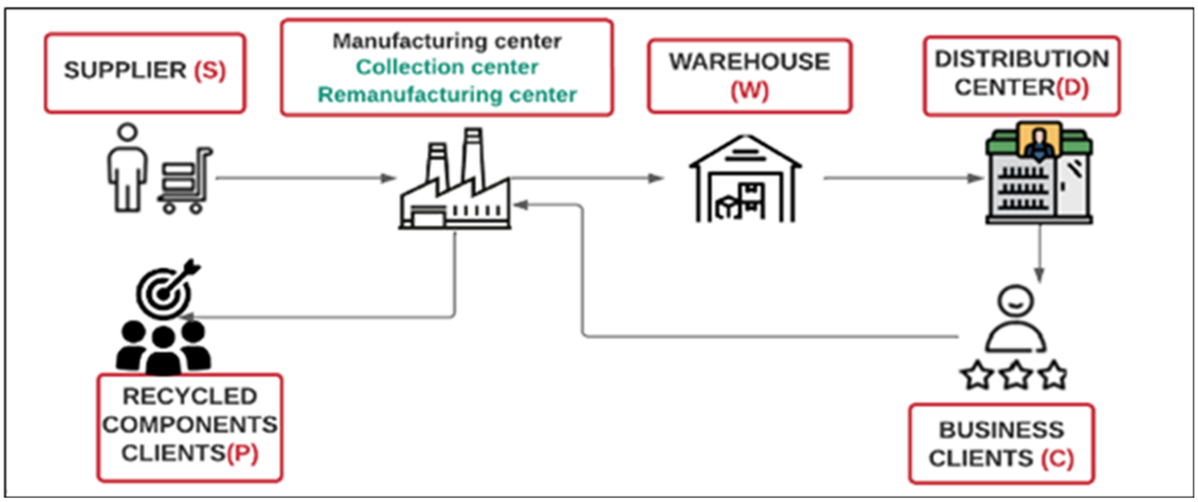


Figure 3.3 The CLSC configuration in Case 1

The second case considers to locate the collection and recycling centers in the same (new) facility, as shown in figure 3.4. In this case, the investment includes opening a new collection and recycling center with the necessary space area, technologies, machinery, and human resources to collect/store used medical face masks and produce/sell polypropylene pellets.

Case 3 considers to locate the collection center and the (existing) warehouse in the same location, and to locate the recycling and the (existing) manufacturing centers in the same location, and finally, to locate the recycling and the (existing) manufacturing centers in the same facility as shown in figure 3.5. Investments in case 3 are related to the costs of the warehouse size extension, and to technologies, machinery, and human resources investments needed for a collection center.

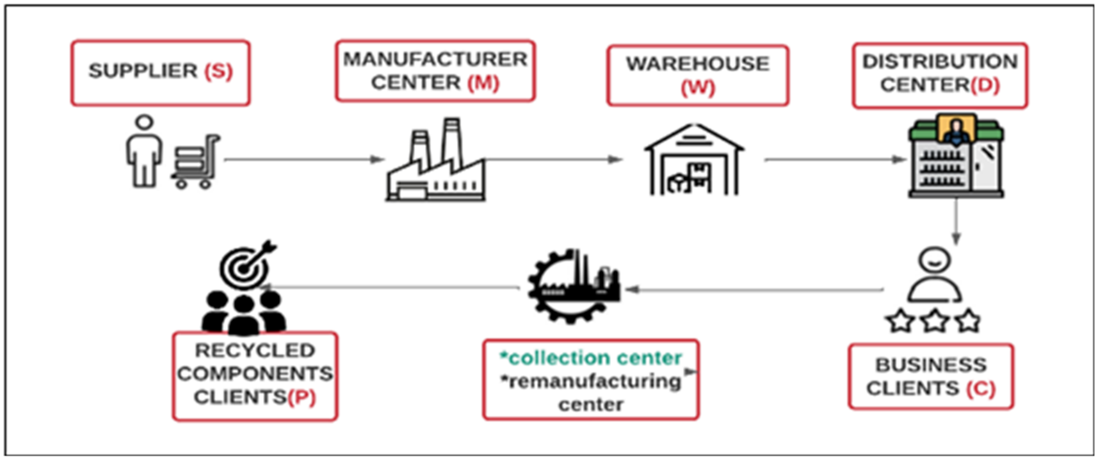


Figure 3.4 The CLSC configuration in Case 2

Extra investments needed for establishing the recycling center in the same facility as the existing manufacturing center (space area, technology, machinery, and human resources) are also considered.

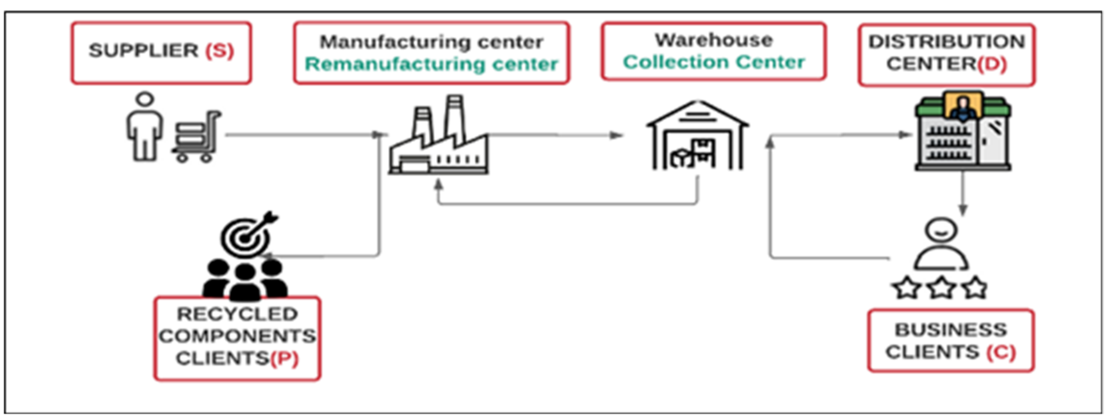


Figure 3.5 The CLSC configuration in Case 3

The fourth case considers locating the collection center and the warehouse in the same facility (existing warehouse) and opening a new facility for the recycling center, as shown in figure 3.6. Investments in Case 4 include the costs of the warehouse size extension, and technology, machinery, and human resources investments needed for the collection center.

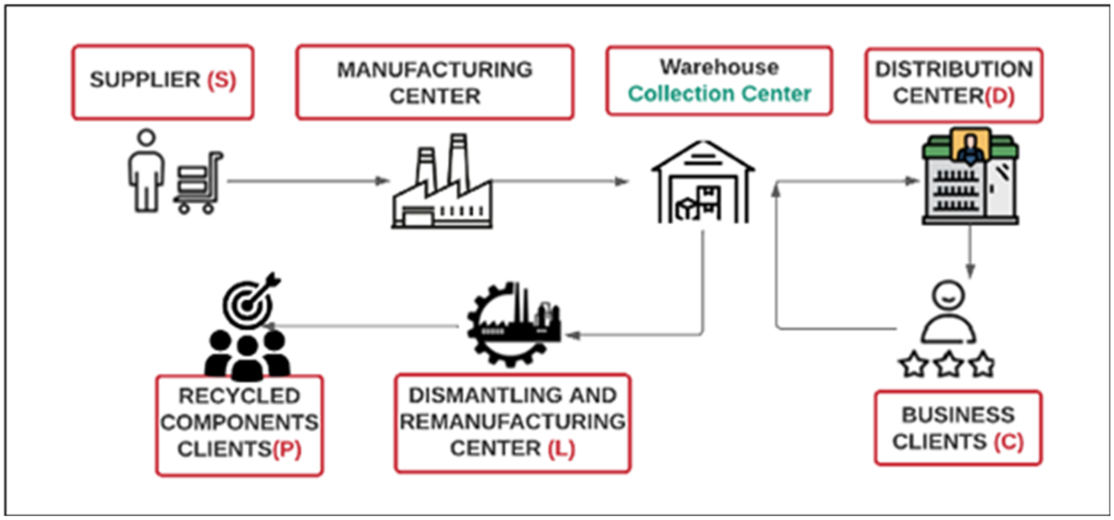


Figure 3.6 The CLSC configuration in Case 4

Finally, case 5 (figure 3.7) is based on a RLN configuration, where the business clients of medical face masks (Cases 1 to 4) are now the suppliers of raw materials (used medical face masks) for the collection and recycling centers (both located in the same new facility to establish). This case encompasses two sub-cases, Case 5A where only polypropylene is recycled a Case 5B where aluminum is also recycled in addition to polypropylene. The investments encompass the costs required to open a new facility equipped with the necessary technologies, machinery, and human resources for collecting/storing the used medical face masks and manufacturing polypropylene pellets and aluminum.

Figure 3.7 The RLN configuration in Case 5

Each of these five cases presents three different scenarios. The parameter that varies within these three scenarios is the percentage of returned (collected) used medical face masks. All other parameters remain fixed (see Table 3.1).

Table 3.1 Parameters of the scenarios considered

Demand of clients (number of boxes)	Selling price of masks (for 1 box) *	Selling price of polypropylene (for 1 kg) **
999,000	$12	$1.66
Percentage of returned medical face masks per scenario		
80%	50 %	25%
Scenario 1.1,4,7,10,13	1.2,5,8,11,14	1.3,6,9,12,15

*This parameter is not considered in case 5.
** In case 5B, we consider also selling aluminum ($2.10 per kg)

The assumptions of our study are the following:

- There is no material loss in the disassembly process.
- There is no material loss in transforming filters to polypropylene pellets.
- Inventories are not considered
- Elastic components are not recycled in any Case.
- Aluminum components are not recycled in Case 1 to Case 4, and Case 5A.
- Aluminum component is recycled in cases 5.2.
- The decontamination process is included in the dismantling process in the remanufacture center.
- The planning horizon duration is one year.
- There exists an established list of potential suppliers for the raw materials (i.e., the cost of selecting a given supplier is relatively low).
- The location of the forward logistics facilities (warehouse, manufacturing, and distribution centers) is predetermined.

- The location of the other RL facilities (collection and recycling centers) are determined based on the results in terms of profitability of the different SC configuration cases (based on the profit and ROI indicators). The best configuration would indicate the location of the these too facilities.

3.2 Mathematical model formulation

To address the aforementioned problem, we formulated a mixed integer linear programming model (MILP) that maximizes the total profit of the SC. The reason for choosing profit maximization instead of cost minimization was for analysing profitability and economic feasibility. This approach not only allows for calculating the profit, but facilitates also ROI calculation ana analysis for decision-makers (ROI calculation is based on profit). Note that, we used this model for cases 1 to 4, and specifically for cases 5A and 5B, we keep just the RL part starting from business clients to potential clients of the recycled components (as shown in figure 3.7). The sets, indices, parameters, decision variables, objective function and constraints are as follows:

3.2.1 Sets and indices

S	Set of suppliers
M	Set of manufacturing centers
W	Set of warehouses
D	Set of distribution centers
C	Set of business clients

A	Set of collection centers
L	Set of recycling centers
P	Set of clients for recycled components
R	Set of raw materials
V	Set of recycled components

3.2.2 Decisions variables

$\mathbf{SM_{smr}}$	Flow of component r between supplier s and manufacturing center m (number of rolls)
$\mathbf{MW_{mw}}$	Flow of medical face masks between manufacturing center m and warehouse w (number of boxes, 1 box = 50 masks)
$\mathbf{WD_{wd}}$	Flow of medical face masks between warehouse w and distribution center d (number of boxes)
$\mathbf{DC_{dc}}$	Flow of medical face masks between distribution center d and business client c (number of boxes)
$\mathbf{CC_{ca}}$	Flow of used medical face masks between business clients c and collection center a (in terms of kgs)
$\mathbf{CR_{al}}$	Flow of used medical face masks between collection center a and recycling center l (kgs)
$\mathbf{RP_{lpv}}$	Flow of recycled materials v between recycling center l and client p (kgs)

$\mathbf{Y_{sr}}$	Binary variable equals 1 if supplier s is selected for raw material r, 0 otherwise

3.2.3 Parameters

PCrs	Procurement cost of 1 unit of component r from supplier s (1 unit =1 roll)
MC	Manufacturing cost of 1 unit of medical face mask (1unit =1box =50 masks)
RCv	Recycling cost of 1 unit of recycled component v (1 unit =1 kg)
Csr	Shipping capacity of supplier s for component r (number of rolls)
***D*c**	Medical face mask demand (in number of boxes) of business client c
$\propto$**c**	% of returned medical face masks by business client c
Qm	Capacity of manufacturing center m (number of boxes)
Kl	Capacity of recycling center l (kgs)
KKa	Capacity of collection center a (kgs)
Hr	The amount of component r required to produce 1 unit of medical face masks (in terms of fraction of number of rolls)

HHv	The amount of recycled component v present in 1 kg of medical face masks (in terms of %)
Pm	Selling price for 1 unit of medical face masks ($/1 box)
PP	Selling price for 1 unit of polypropylene ($/1 kg)
$\boldsymbol{TCSM_{sm}}$	Transportation cost of 1 unit of medical face masks per km between supplier s to manufacturing center m 1 unit is equal to 50 medical face masks which is equivalent to 0.154 kgs
$\boldsymbol{TCMW_{mw}}$	Transportation cost of 1 unit of medical face masks per km between manufacturing center m to warehouse w
$\boldsymbol{TCWD_{wd}}$	Transportation cost of 1 unit of medical face masks per km between warehouse w to distribution center d
$\boldsymbol{TCDC_{dc}}$	Transportation cost of 1 unit of medical face masks per km between distribution center d to business clients c
$\boldsymbol{TCCA_{ca}}$	Transportation cost of 1 unit of medical face masks per km between business clients to collection center a
$\boldsymbol{TCAl_{al}}$	Transportation cost of 1 unit of medical face masks per km between collection center a to dismantling and remanufacturing center l
$\boldsymbol{DSM_{sm}}$	Distance in kms between supplier s to manufacturing center m (in terms of kms)

$\boldsymbol{DMW_{mw}}$	Distance in kms between manufacturing center m to warehouse w (in terms of kms)
$\boldsymbol{DWD_{wd}}$	Distance in kms between warehouse w to distribution center d (in terms of kms)
$\boldsymbol{DDC_{dc}}$	Distance in kms between distribution center d to business clients c (in terms of kms)
$\boldsymbol{DAL_{al}}$	Distance between collection center a and dismantling and remanufacturing center l (in terms of kms)
$\boldsymbol{DCA_{ca}}$	Distance in kms between business clients to collection center a (in terms of kms)
$\boldsymbol{TSM_{sm}}$	Transportation capacity between supplier s to manufacturing center m (in terms of kgs)
$\boldsymbol{TMW_{mw}}$	Transportation capacity between manufacturing center m to warehouse w (in terms of kgs)
$\boldsymbol{TWD_{wd}}$	Transportation capacity between warehouse w to distribution center d (in terms of kgs)
$\boldsymbol{TDC_{dc}}$	Transportation capacity between distribution center d to business clients c (in terms of kgs)
$\boldsymbol{TCA_{ca}}$	Transportation capacity between business clients to collection center a (in terms of kgs)

$\boldsymbol{TAL_{al}}$	Transportation capacity between collection center a to dismantling and remanufacturing center l (in terms of kgs)
FFrs	Fixed cost to select a supplier s
X	Conversion factor (0.154 kgs =1 box of 50 masks)

It should be noted that all costs and revenues are denominated in Canadian dollars. One box of 50 dollars corresponds to 0.154 kilograms. We assume that there is already an established list of potential suppliers, which is why the cost associated with selecting these suppliers is not very high.

3.2.4 Objective function

$$Max\ \ Z = \sum_{d\in D}\sum_{C\in C}(DC_{dc} * PM)\ + \sum_{l\in L}\sum_{p\in P}\sum_{\substack{v\in V\\ a}}\left(RP_{lpv} * PP\right) \tag{3.1}$$

$$-\sum_{r\in R}\sum_{s\in S}\sum_{m\in M}(SM_{smr} * PC_{rs})\ \ -\sum_{m\in M}\sum_{w\in W}(MW_{mw} * MC) \tag{3.2}$$

$$-\sum_{s\in S}\sum_{m\in M}\sum_{r\in R}(SM_{smr} {}_{*} TCSM_{sm} * DSM_{sm}) \tag{3.3}$$

$$-\sum_{m\in M}\sum_{w\in W}(MW_{mw} * TCMW_{mw} * DMW_{mw}) \tag{3.4}$$

$$-\sum_{w\in W}\sum_{d\in D}(WD_{wd} * TCWD_{wd} * DWD_{wd}) \tag{3.5}$$

$$-\sum_{d\in D}\sum_{c\in C}(DC_{dc} * TCDC_{dc} * DDC_{dc}) \tag{3.6}$$

$$-\sum_{c\in C}\sum_{a\in A}(CC_{ca} * TCCA_{ca} * DCA_{ca}) \tag{3.7}$$
$$-\sum_{a\in A}\sum_{l\in L}(CR_{al} * TCAl_{al} * DAL_{al})$$

$$-\sum_{l\in L}\sum_{p\in P}\sum_{\substack{v\in V\\ v=1}}\left(RC_{v} *\ RPL_{pv}\right) \tag{3.8}$$

$$-\sum_{S}\sum_{R}(Y_{sr} * FF_{rs}) \tag{3.9}$$

3.2.5 Constraints

$$\sum_{m\in M} SM_{smr} \leq Y_{sr} *\ C_{sr} \qquad \forall s\ \in S\ , r\ \in R \tag{3.10}$$

$$\sum_{d\in D} DC_{dc} = D_{C} \qquad \forall c\ \in\ C \tag{3.11}$$

$$\sum_{a\in A} CC_{a} = \sum_{d\in D} DC_{dc} *\propto_{c} * X \qquad \forall c\ \in\ C \tag{3.12}$$

$$\sum_{w\in W} MW_{mw} \leq q_{m} \qquad \forall m\ \in\ M \tag{3.13}$$

$$\sum_{c\in C} CC_{ca} \leq\ KK_{a} \qquad \forall a\ \in\ A \tag{3.14}$$

$$\sum_{a\in A} CR_{al} \leq K_l \qquad \forall l \in L \tag{3.15}$$

$$\sum_{s\in S} SM_{smr} = \sum_{w\in W} MW_{mw} * H_r \qquad \forall r \in R, m \in M \tag{3.16}$$

$$\sum_{m\in M} MW_{mw} = \sum_{d\in D} WD_{wd} \qquad \forall w \in W \tag{3.17}$$

$$\sum_{a\in A} CR_{al} * HH_v = \sum_{p\in P} RP_{lpv} * X \qquad \forall\ l \in L, \quad v \in V \tag{3.18}$$

$$\sum_{c\in C} CC_a = \sum_{l\in L} CR_{al} \qquad \forall a \in A \tag{3.19}$$

$$\sum_{w\in W} WD_{wd} = \sum_{c\in C} DC_{dc} \qquad \forall d \in D \tag{3.20}$$

$$SM_{smr} \leq TSM_{sm} \qquad \forall m \in M, w \in W \tag{3.21}$$

$$MW_{mw} \leq TMW_{mw} \qquad \forall m \in M, w \in W \tag{3.22}$$

$$WD_{wd} \leq TWD_{wd} \qquad \forall d \in D, w \in W \tag{3.23}$$

$$DC_{dc} \leq TDC_{dc} \qquad \forall d \in D, c \in C \tag{3.24}$$

$$CC_{ca} \leq TCA_{ca} \qquad \forall a \in A, c \in C \tag{3.25}$$

$$CR_{al} \leq TAL_{al} \qquad \forall a \in A, l \in L \tag{3.26}$$

$$SM_{smr,}\ MW_{mw,}\ WD_{wd,}\ DC_{dc,}\ CC_{ca,}\ CR_{al,}\ \ RP_{lpv} \geq 0 \tag{3.27}$$

$$Y_{sr}\ \{0,1\} \qquad \forall s \in S, r \in R \tag{3.28}$$

The objective function (summation of the terms 3.1 to 3.9) maximizes the total profit of the SC that includes total revenues generated from selling medical face masks and recycled components (3.1) minus total costs composed of procurement, manufacturing (3.2), transportation (3.3 to 3.7), recycling (3.8), and supplier selection costs (3.9).

Constraints (3.10) ensure the respect of the suppliers' capacities. Constraints (3.11) indicate that the demand for medical face masks must be satisfied for each client. Constraints (3.12) restrict for each client the amount of collected used medical face masks (expressed in % of the quantity of medical face masks received, i.e., we assume that not all the quantity of used medical face masks is collected). Constraints (3.13) ensure the respect of the production capacity of the manufacturing centers. Constraints (3.14) ensure the respect of the collection centers' capacities. Constraints (3.15) assure the respect of the recycling centers' capacities. Constraints (3.16) guarantee that demands of manufacturing centers for raw materials are respected (for each facility and raw material type). Constraints (3.17) indicate that the inflow of a warehouse does not exceed the total flows sent from the manufacturing centers to that warehouse. Constraints (3.18) indicate that the amount of recycled components (sold to clients) is equal to the amount recovered from collected used medical face masks. Constraint (3.19) indicate that all medical face masks collected at the collection centers must be transported to the recycling centers. Constraints (3.20) assure that the flows between the warehouses and the distribution centers are the same from distribution center to business clients (flow balance constraints). Constraints (3.21-3.26) ensures that the flows between the facilities do not exceed the transportation capacity. Finally, constraint (3.27) ensures that the decision variables are positive and continuous, and constraints (3.28) that the decision variables related to supplier selection are binary.

CHAPTER 4

EXPERIMENTS AND RESULTS

This chapters presents the data collection process for building our case study, the results of the model solved on the basis of the case study, and the conditions under which the SC can achieve profitability. Such conditions include for example the location of the collection and recycling centers, the % of used medical face masks to collect and establishing a CLSC or only a RLN. Finally, a sensitivity analysis is performed. The purpose of the sensitivity analysis is to evaluate the impact of uncertainty in different projections of the investments required for different SC configuration cases and scenarios.

4.1 Process of data collection

The process of collecting and validating the data comprised different phases. First, we identified the key business sectors within our SC. These included:

1. The manufacturing sector, represented by a company responsible for producing medical face masks, which granted us access to specific manufacturing / raw material supply processes, parameters, and data. Additionally, it was essential to understand the current state of this industry and identify the most critical logistics and manufacturing challenges that manufacturers face such as the rapid reaction to meet the overwhelming demand for medical face masks and the capacity to pivot during a global pandemic when sourcing raw materials became challenging, along with the adaptation of various industries to produce medical face masks in support of the worldwide health crisis

2. The recycling sector, represented by a company responsible for recycling medical face masks, among other products. The information provided by this company was specific recycling costs, bill of materials, capacities and geographical locations and transportation data.

3. The logistics sector responsible for the collection and transportation of the medical face masks. A company specializing in collecting and recycling products dangerous to health and the environment gave us information about rate of return of used medical face mask, capacities and geographical location, and of transportation data

4. The client, represented by an educational institution (ÉTS), gave us the number of medical face masks used by students and employees.

As an additional source of information, we used the report produced by a student who gathered pertinent information concerning medical face masks used in the healthcare sector and the manufacturing and recycling process of medical face masks (Clermont-Beaudoin, 2021). Moreover, the recycled component costs were obtained with the support of statistical data and cost reports related to waste management, recycling, and the plastic recycling industry in Canada (*Resin Prices*, 2023). Note that most of the data collected from our industrial collaborators can not be disseminated in this thesis for confidentiality reasons.

The subsequent phase involved identifying a person responsible for each sector. Initial contact was made via emails and phone calls. Occasionally, multiple emails were necessary before receiving a response.

The third phase involved face-to-face videoconference meetings focused on identifying the variables and parameters data of the analysis. Notably, previous literature research on the medical face mask SC contributed to more dynamic sessions, facilitating clarification on specific points with the industrial representatives. We carefully gathered the relevant information from our industrial partners, culminating in the creation of a checklist outlining the necessary information for our model. The fourth phase involved maintaining continuous follow-up to refine the information. The information requested was quantitative and qualitative, for example the geographical location of the companies, procurement costs, manufacturing cost, remanufacturing cost, transportation cost, production capacities, demand, bill of materials, medical face masks and polypropylene selling prices. The fifth phase consisted of adjusting the data to make it coherent across all companies, which necessitated unit conversions and standard measurements to regulate the entire SC. It is important to highlight that continuous communication and feedback were maintained among all involved parties throughout this process. Finally, a meeting was held with the parties involved to show the preliminary results of our model, and thanks to their feedback, the validation of both, the data and results was achieved.

4.2 Results of the mathematical model

The problem was solved by using IBM ILOG CPLEX 20.1 on a lap-top with the processor Intel i5-1035G1 and a RAM capacity of 12 Gb. As we mentioned in Chapter 3, three different scenarios within each case (1 to 5) are analyzed based on the parameters presented in Table 3.1 (15 scenarios in total). Our aim is to evaluate which scenarios and cases yield the highest profits and best ROI. ROIs (measured in %) is calculated by dividing the total profit (i.e., mathematical model output) by the investment required for each SC configuration of each case (and scenario). ROI is a valuable metric used to evaluate the performance of an investment (*Roi-Metric,2009*). The investments are estimated based on the fixed costs required to open a new facility or extending an existing one (see Section 3.1) in a planning horizon of 5 years. The results of cases 1, 2, 3, 4, and 5 are shown in Table 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6, respectively.

For case 1 (Table 4.1), the results show that all scenarios are profitable. The percentage of returned medical face masks does not have a significant impact on the profit, and therefore on the ROI. However, recycling aluminum was not considered (cases 1 to 4 and 5A). Otherwise, the profit and ROI would be slightly higher (this aspect is analyzed in case 5.2). Scenario 1.1 is the best with a ROI of 55.28%.

Table 4.1 Results of case 1 (scenarios 1.1, 1.2, and 1.3)

% of returned (used) masks	**80**	**50**	**25**
Scenario	**# 1.1**	**# 1.2**	**# 1.3**
Procurement cost ($)	1,958,345.44	1,958,345.44	1,958,345.44
Manufacturing cost ($)	3,849,147	3,849,147	3,849,147
Transportation cost ($)	219,606.97	217,299.28	215,376.20
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Supplier selection cost ($)	600	600	600
Total cost ($)	6,190,616.33	6,127,214.79	6,074,380.18
Revenues from selling medical face masks ($)	11,988,000	11,988,000	11,988,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total revenue ($)	12,188,327.4	12,113,204.6	12,050,602.3
Total profit ($)	5,997,711.14	5,985,989.88	5,976,222.15
Total investment ($)	10,850,000	10,850,000	10,850,000
ROI (%)	55.28	55.17	55.08

Table 4.2 shows that all scenarios within case 2 are profitable. The best scenario, in this case is scenario 2.4, with an ROI of 42.80%. All scenarios of case 3 are profitable (Table 4.3). The best scenario is #7, with an ROI of 56.21%.

Table 4.4 shows that all scenarios in case 4 are profitable. The best scenario, in this case, is scenario 4.10, with an ROI of 49.88%.

Table 4.2 Results of case 2 (scenarios 2.4, 2.5, and 2.6)

% of returned (used) masks	**80**	**50**	**25**
Scenario	**# 2.4**	**# 2.5**	**# 2.6**
Procurement cost ($)	1,958,345.44	1,958,345.44	1,958,345.44
Manufacturing cost ($)	3,849,147	3,849,147	3,849,147
Transportation cost ($)	225,199.69	222,892.00	220,968.92
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Supplier selection cost ($)	600	600	600
Total cost ($)	6,196,209.05	6,132,807.51	6,079,972.90
Revenues from selling medical face masks ($)	11,988,000	11,988,000	11,988,000
Total revenue ($)	12,188,327.4	12,113,204.6	12,050,602.3
Total profit ($)	5,992,118.42	5,980,397.16	5,970,629.43
Total investment ($)	14,000,000	14,000,000	14,000,000
ROI (%)	42.80	42.72	42.65

Table 4.3 Results of case 3 (scenarios 3.7, 3.8, and 3.9)

% of returned (used) masks	**80**	**50**	**25**
Scenario	**# 3.7**	**# 3.8**	**# 3.9**
Procurement cost ($)	1,958,345.44	1,958,345.44	1,958,345.44
Manufacturing cost ($)	3,849,147	3,849,147	3,849,147
Transportation cost ($)	231,352.84	226,737.11	222,891.78
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Supplier selection cost ($)	600	600	600
Total cost	6,202,362.20	6,136,653.23	6,081,895.76
Revenues from selling medical face masks ($)	11,988,000	11,988,000	11,988,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total profit ($)	5,985,965.27	5,976,551.44	5,968,706.57
Total investment ($)	10,650,000	10,650,000	10,650,000
ROI (%)	56.21	56.12	56.04

Table 4.4 Results of case 4 (scenarios 4.10, 4.11, and 4.12)

% of returned (used)masks	**80**	**50**	**25**
Scenario	**# 4.10**	**# 4.11**	**# 4.12**
Procurement cost ($)	1,958,345.44	1,958,345.44	1,958,345.44
Manufacturing cost ($)	3,849,147	3,849,147	3,849,147
Transportation cost ($)	231,353.53	226,738.15	222,892.53
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Supplier selection cost ($)	600	600	600
Total cost ($)	6,202,362.89	6,136,653.66	6,081,895.98
Revenues from selling medical face masks ($)	11,988,000	11,988,000	11,988,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total revenue ($)	12,188,327.4	12,113,204.6	12,050,602.3
Total profit ($)	5,985,964.58	5,976,551.01	5,968,706.57
Total investment ($)	13,500,000	13,500,000	13,500,000
ROI (%)	44.34	44.27	44.21

For case 5A, the revenue generated from selling polypropylene lead to a positive profit (Table 4.5). All scenarios are profitable. However, the ROIs are very low. Case 5.2 generates an additional revenue (from recycling and selling aluminum), which leads to a slight increase in profits and ROIs (Table 4.5). The purpose of including aluminum is to assess how it would impact the SC profitability.

Cases 5A and 5B lead to very low profits and ROIs even in the best scenario (#16; ROI = 0.49%). This means that it is not profitable to establish a RLN without integrating it with the forward logistics. To address this situation, the investment should be lower, for example by obtaining a governmental subsidy.

Table 4.5 Results of cases 5A and 5B (scenarios 5.13, 5.14, 5.15, 5.16, 5.17, and 5.18)

% of returned (used) medical face masks	**80**	**50**	**25**
Scenarios of Case 5A	**#5.13**	**#5.14**	**#5.15**
Transportation cost ($)	6,153.84	3846.15	1,923.075
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Total cost ($)	169,070.76	105,669.23	52,834.61
Total investment ($)	7,000,000	7,000,000	7,000,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total profit ($)	31,256.71	19,535.44	9,767.73
ROI (%)	0.44%	0.27%	0.13%
Scenarios of Case 5B	**#5.16**	**#5.17**	**#5.18**
Revenues from selling polypropylene and aluminum ($)	203,684.11	127,302.57	63,651.29
Total profit ($)	34,613.35	21,633.35	10,816.67.
ROI (%)	0.49%	0.30%	0.15%

4.3 Sensitivity analysis

We performed a sensitivity analysis on the scenarios with the highest ROI in each case, by varying the estimated investment from 10% up to 100% above its initial value. Since the required investments in different cases are based on estimations. In scenario 5, a sensitivity analysis is conducted by adjusting the projected investment from -80% to 80%. This assessment aims to explore the potential outcomes if a financial support is obtained from the government or other organizations. It is essential to determine how varying the investment values would impact the SC profitability. The results of cases 1 (scenario 1.1), 2 (scenario 2.4), 3 (scenario 3.7), 4 (scenario 4.10), and 5 (scenario 5.14) are shown in figures 4.1, 4.2, 4.3, 4.4, and 4.5 respectively.

The sensitivity analysis (see Figure 4.1) shows that even in the worst case, we obtain a good ROI (27,64%).

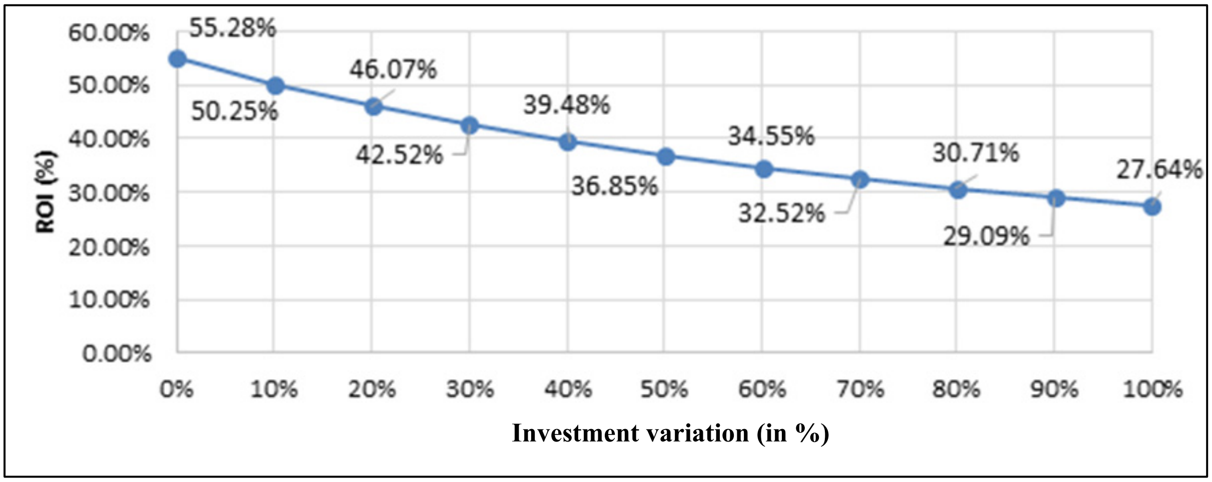


Figure 4.1 Results of the sensitivity analysis (Case 1, scenario 1.1)

Our sensitivity analysis (Figure 4.2) reveals that even in the worst case, we continue to obtain a good value of the ROI (21,40%).

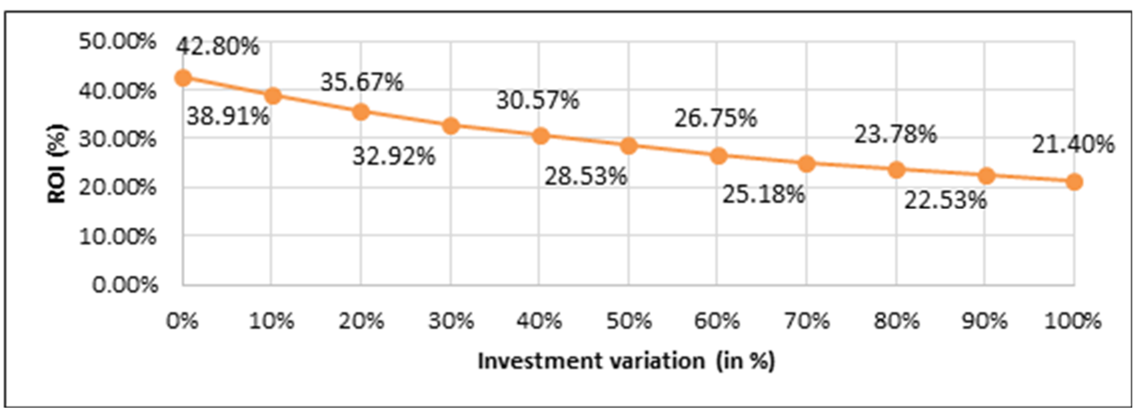


Figure 4.2 Results of the sensitivity analysis (Case 2, scenario 2.4)

Figure 4.3 shows even in the worst case, the ROI value is rather good (28,10%)

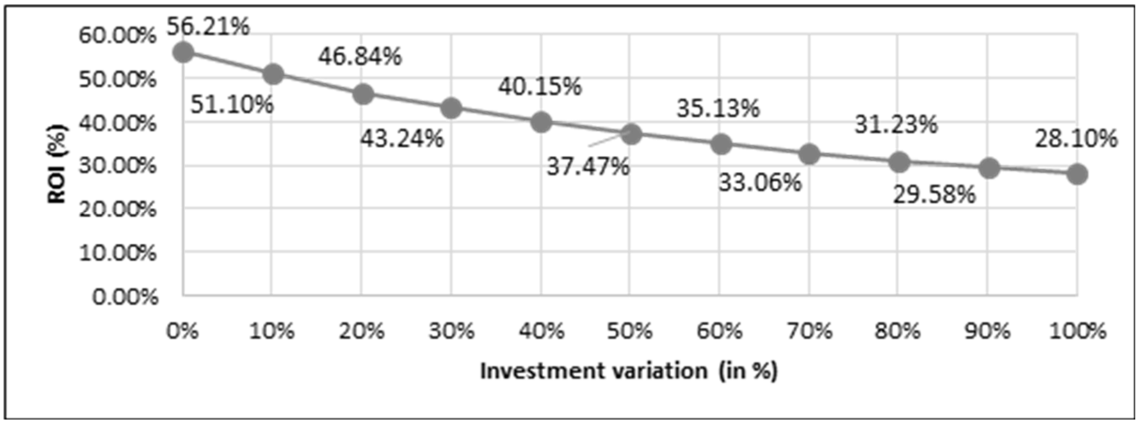


Figure 4.3 Results of the sensitivity analysis (Case 3, scenario 3.7)

Again, we observe that we continue to have a rather good ROI even in the worst case (22.17%) (see Figure 4.4).

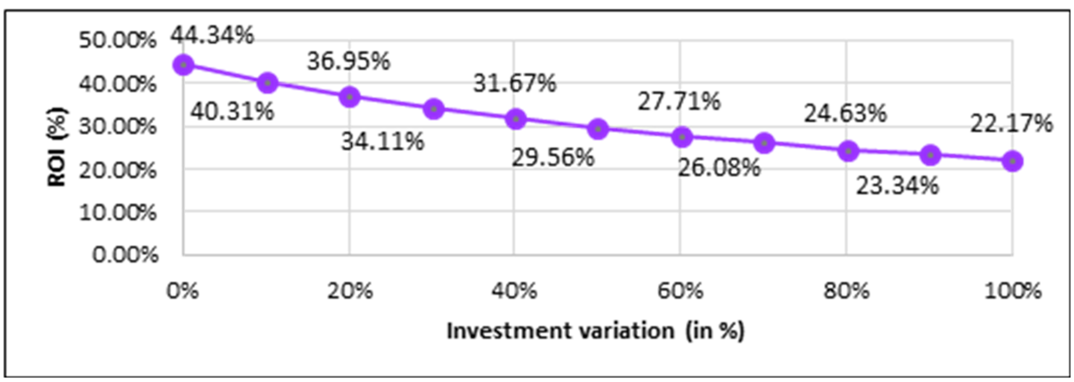


Figure 4.4 Results of the sensitivity analysis (Case 4, scenario 4.10)

Our sensitivity analysis on the investment (see Figure 4.5) shows that the ROI could increase up to 2.47% if the investment is lower than the initial value by 80%. In this case of RL is also considered an investment of -80% in the case that financial support is obtained from some institution or government.

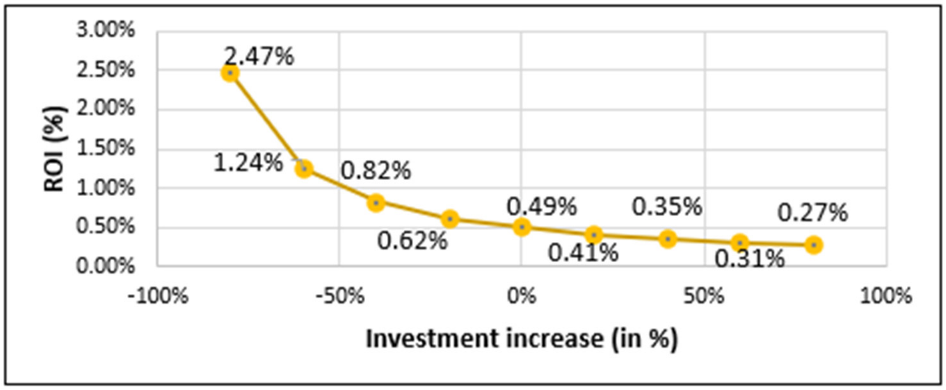


Figure 4.5 . Results of the sensitivity analysis (Case 5B, scenario 5.16)

4.4 Return on investment with economies of scale

This subsection analyzes the conditions that lead to an economically viable medical face mask SC with a desired ROI. The objective is to find the quantity of medical face masks that must be collected and recycled to obtain this desired ROI. A desired ROI depends on several factors, such as the amount of the initial investment, the quantity and selling prices of recycled components, market demand, government incentives, etc. In the field of waste management, the ROI for 2020 to 2023 ranged from 8.5% to 11% (WM macrotrends, 2023). It was found that around 20% of the initiatives to collect plastic met a benchmark of 15% ROI or greater for recycling (Gao et al., 2020). Therefore, this study analyzes a scenario with an ROI of 10%. In particular, this section focuses on case study 5, where the RLN is analyzed. This is because the results in the previous chapter 4 indicate that RLN is not profitable enough. The following subsections show the data collection process and the relevant calculations performed to obtain the quantity of used masks to collect and recycle to ensure a ROI of 10%.

4.4.1 Data and parameters

To collect the data, we collaborated with an industrial with ten years of experience in the plastics transformation and manufacturing sector. The communication was by email and telephone calls. Moreover, the recycled component costs were obtained with the support of statistical data and cost reports related to waste management, recycling, and the plastic recycling industry in Canada (*Resin Prices*, 2023).

The fixed investment includes investment in tangible fixed assets, such as purchase and construction for the installation of the recycling plant or rental of space for it, as well as the acquisition of furniture, equipment, and machinery that allows us to convert used medical face masks into polypropylene pellets. This machinery includes the conveyor metal detector, separator, pumping, reactor, extruder, and palletizing machine. The fixed investment allows us to have the necessary conditions for the recycling plant to begin its operations, which are independent of the production volume. On the other hand, variable investments are dependent of the volume of polypropylene manufactured. We consider different possible production capacities for the recycling plant, and for each production capacity, there is a specific variable investment that decreases according to incremental EOS. For example, if the production capacity is X1, we will pay a cost C1 for every produced unit up to X1. If the production capacity is X2 (higher than X1), the difference in units produced between X2 and X1 will be paid at a lower cost of C2, etc. As the production capacity increases, the average cost per unit decreases, making each unit more cost-effective to produce (Nahmias, 2009).

Below, are presented the parameters required to perform our calculations.

Z Profit (same formula as the objective function presented in subsection 3.2.4)

INF Fixed investment

$INVn$ Variable investment corresponding to different production capacities "Xn"; where n = 1, 2, 3, etc.

RP_{lpv} Quantity of recycled medical face masks (in kgs). This is the quantity that we aim to calculate for a desired ROI.

TI Total Investment (summation of fixed investment and variable investment)

PP Selling price of recycled polypropylene component (same as the parameter presented in subsection 3.2.3)

PAL Selling price of recycled aluminum component (same as the parameter presented in subsection 3.2.3)

4.4.2 Cost function development

The objective is to determine the amount of used medical face masks to recycle (into polypropylene and aluminum) that need to be collected to obtain a desired ROI (10% in our case). To do so, we consider that the variable investments are proportional to the quantity of recycled components following incremental EOS (Equation 4.1).

$$INVn = INV1 * RP_{lpv}1 + INV2 * (RP_{lpv}2 - RP_{lpv}1) + INV3 * (RP_{lpv} - RP_{lpv}2) \quad (4.1)$$

Note that we consider three production capacities (X1, X2, and X3). The main calculation steps leading to Equation (4.6) that seeks to find the amount of recycled medical face masks needed to obtain the desired ROI, are presented below.

$TI = INF + INVn$ (4.2)

$Z = (HH_V * RP_{lpv} * PP + HH_V * RP_{lpv} * PAL) -$
$(RP_{lpv} * TCIJ_{ij} * DIJ_{ij} + RP_{lpv} * RC_v)$

In other terms: (4.3)

$Z = RP_{lpv} * (HH_V * PP + HH_V * PAL) - \left(TCIJ_{ij} * DIJ_{ij} + RC_v\right)$

On the other hand, $ROI = \frac{Z}{TI}$ (4.4)

Therefore: $Z = ROI * TI$

$Z = ROI* (INF + INV1 * RP_{lpv}1 + INV2* \left(RP_{lpv}2 - RP_{lpv}1\right)$ (4.5)
$+INV3(RP_{lpv} - RP_{lpv}2)$

By solving the system of equations (4.3) and (4.6), we obtain:

$$RP_{lpv} = \frac{ROI * INF + ROI * INV1 * RP_{lpv}1 + \mathrm{ROI} * \mathrm{INV2} * RP_{lpv}2 - ROI * INV2 * RP_{lpv}1 - \mathrm{ROI} * \mathrm{INV3} * RP_{lpv}2}{(HH_V * PP + HH_V * PAL) - \left(TCIJ_{ij} * DIJ_{ij} + RC_v\right)(1 - ROI * INV3)} \quad (4.6)$$

The data used to perform the calculations is summarized in Table 4.6

Table 4.6 Investment data used

ROI =10 %	Production capacities
Fix Investment = $7,500,000	
Variable Investment1 = 0.05 per unit	X1 ≤10,000,000 kgs
Variable Investment2 = 0.03 per unit	10,000,000 < X2 ≤ 20,000,000 kgs
Variable Investment3 = 0.01 per unit	X3 > 20,000,000 kgs

The results show that to obtain an ROI of 10%, it is necessary to convert 10,062,111.8 kgs of used medical face masks in polypropylene pellets and sell them in the market (aluminium as well), which means that a facility with a capacity ranging between 10,000,000 and 20,000,000 kgs would be required

4.5 Conclusion

Overall, the best profit and ROI are obtained in case 3 and scenario 3.7, where the warehouse also serves as a collection center, the recycling center is located in the same location as the manufacturing center, and 80% of used medical face masks is collected. The ROI in this scenario is 56.21%. Therefore, this would be the best scenario for the decision makers who would like to invest in this project, and the most profitable SC configuration is a CLSC one. The revenues come mainly from selling medical face masks in this case. The results in cases 5A and 5B reveal that it is not reasonable to establish a RLN for collecting and recycling used medical face masks without integrating it with the forward SC or decreasing the investment required for medical face mask collection and recycling. This latter could be possible if a substantial governmental subsidy is granted to the company interested in investing in this project (conditions of RLN economic feasibility). Another element that improves profitability is sharing existing facilities (warehouse and manufacturing centers) for collecting and recycling the used medical face masks, since this decreases the investments. Another possibility is to collect 10,062,111.8 kgs of used medical face masks to ensure a desired ROI of 10%. In other words, a facility with a capacity ranging between 10,000,000 and 20,000,000 kgs is required.

CONCLUSION AND FUTURE PERSPECTIVES

In this study, we explored the possibility of finding viable solutions for medical face mask collection and recycling at the end of their useful life. We have considered addressing this problem through the logistics perspective by establishing the best configuration of a RLN or a CLSC and determining the most efficient path to collect, recycle and sell the recycled components. The goal was to provide decision-makers with the conditions under which the SC of recycled medical face masks is profitable. The business units considered in this SC are the suppliers, manufacturing center, warehouse, distribution center, business clients, collection center, recycling center, and clients for recycled components. The main contribution of this study is the scenario and sensitivity analysis proposed to find the conditions ensuring profitability and economic feasibility, based on a realistic case study in the Montreal region.

Our scenarios consider five different configurations of the SC (CLSC and RLN) three different rates of returned medical face masks, and two recycled components (polypropylene and aluminum). The results show that it is not reasonable to establish a for collecting and recycling medical face masks unless it is integrated with the forward SC or a substantial governmental subsidy is granted. One of the elements that increases the profitability of the SC is expanding and sharing existing facilities (warehouse and manufacturing centers) for collecting and recycling used medical face masks. The results show that to obtain an ROI of 10%, it is necessary to convert 10,062,111.8 kgs of used medical face masks in polypropylene pellets and sell them in the market together with the aluminium, which leads to facility with a capacity ranging between 10,000,000 and 20,000,000 kgs. Including EOS in such as project is essential for companies that want to optimize their operations and remain competitive.

The model proposed in this study could be used as a decision-support tool to guide logisticians and decision-makers in identifying the best configuration of their SC for recycling medical face masks, by considering different parameters, constraints, and scenarios. The model could be also adapted for other products. As a future research direction, we suggest to include the environmental footprint (e.g., carbon emissions) of the SC in the mathematical model to minimize its environmental impact. It would be also relevant to analyze uncertainties related to the data (e.g., demand for medical face masks and quantity of used medical face masks that could be collected). It is also recommended to consider including other recyclable items from the healthcare sector, such as gloves, safety glasses, and specialized surgical suits. Since recycling centers manage a variety of products, analyzing the financial viability linked to recycling a range of items would be valuable and it will be interesting to investigate new ways to use the recycled components from medical face masks in order to create more value. In addition, in the CLSC where the manufacturer is in charge recycling the used medical face masks (CLSC), by selling the polypropylene and aluminum components to their own suppliers, they could receive a discount on the raw materials provided by these suppliers (i.e., internal, external, and middle layers). This would increase the total profit of the manufacturer while benefiting form locally manufactured polypropylene. This could contribute to decreasing the environmental footprint of the medical face mask SC. Moreover, the model could be extended to include binary variables for the location of the collection and recycling centers and determine the optimal design of the RLN or CLSC without having to analyze specific cases as performed in this study. Finally, the estimation of the investments required as well as the EOS could be refined and developed further.

ANNEX I

MODEL CODE IBM CPLEX

```
 *********************************************/
/* Index */

int s_max = ...;
int m_max= ...;
int w_max = ...;
int d_max= ...;
int c_max = ...;
int a_max= ...;
int l_max = ...;
int p_max= ...;
int r_max= ...;
int v_max= ...;


/*2-Sets*/

range S = 1..s_max; /*Set of suppliers*/
range M = 1..m_max; /*Set of Manufacturing centers*/
range W = 1..w_max; /*Set of warehouses*/
range D = 1..d_max; /*Set of distribution centers*/
range C = 1..c_max; /*Set of business clients*/
range A = 1..a_max; /*Set of collection center*/
range L = 1..l_max; /*Set of dismantling and remanufacturing centers*/
range P = 1..p_max; /*Set of  potential clients*/
range R = 1..r_max; /*Set of raw materials*/
range V = 1..v_max; /*Set of reusing components*/


/*2Parameters*/

float pc[ R ][ S ] = ...;/*Procurement cost of 1 unit of component r from
supplier s */
float mc = ...;/*Manufacturing cost of 1 unit of mask 1 unit are 50 masks   */
float rc[ V ] = ...;/*Remanufacturing cost of  1 unit of recycled component v in
Dismantling and remanufacturing center */
float c[ R ][ S ] = ...;/*Shipping capacity of supplier s per component r */
float d[ C ] = ...;/*Mask demand of business client c  */
float alpha[ C ] = ...;/*% of returned masks by business client c */
float q[ M ] = ...;/*Capacity of manufacturing center m */
float k[ L ] = ...;/*Capacity of remanufacturing center l  */
float kk[ A ] = ...;/*Capacity of collection center  */
float h[ R ] = ...;/*The amount of component r required to produce 1 unit of mask
*/
float hh[ V ] = ...;/*The amount of recycled  component v present in 1 unit of
mask  */
```

```
//float f[ L ]= ...;/*Fixed cost opening a new facility at the beginning of
planning horizon*/
float ff[ R ][ S ]=...;/*Fixed cost to select a supplier */
//float fff[ A ]=...;/*Fixed cost opening a new collection center  */
//float fc[ M ]=...;/*Fixed cost opening a new manufacturing center  */
float pm = ...;/*price of selling mask  */
float pp = ...;/*price of selling polypropylene.   */


float tcsm [ S ][ M ] = ...;/*transportation cost of 1 unit of mask  per Km
between supplier to manufacturing center */
float tcmw [ M ][ W ] = ...;/*transportation cost of 1 unit of mask  per Km
between manufacturing center to warehouse*/
float tcwd [ W ][ D ] = ...;/*transportation cost of 1 unit of mask  per Km
between warehouse to Distribution center*/
float tcdc [ D ][ C ] = ...;/*transportation cost of 1 unit of mask  per Km
between Distribution center to business clients  */
float tcca [ C ][ A ] = ...;/*transportation cost of 1 unit of mask  per Km
between business clients to collection center*/
float tcal [ A ][ L ] = ...;/*transportation cost of 1 unit of mask  per Km
between collection center to dismantling and remanufacturing center*/
float tclp [ L ][ P ] = ...;/*transportation cost of 1 unit of mask  per Km
between dismantling and remanufacturing center to potential clients */


float dsm[ S ][ M ] = ...;/* distance in km between supplier and manufacturing
center */
float dmw[ M ][ W ] = ...;/* distance in km between manufacturing center and
warehouse */
float dwd[ W ][ D ] = ...;/* distance in km between warehouse and distribution
center*/
float ddc[ D ][ C ] = ...;/*distance in km between distribution center and
business clients */
float dca[ C ][ A ] = ...;/*distance in km between business clients and
collection center */
float dal[ A ][ L ] = ...;/*distance in km between collection center and
dismantling and remanufacturing center */
float dlp[ L ][ P ] = ...;/*distance in km between dismantling and
remanufacturing center and potencial clients */


float tsm[ S ][ M ] = ...;/*transportation capacity  between supplier and
manufacturing center */
float tmw[ M ][ W ] = ...;/*transportation capacity  between  manufacturing
center to warehouse */
float twd[ W ][ D ] = ...;/*transportation capacity from warehouse to
distribution center*/
float tdc[ D ][ C ] = ...;/*transportation capacity from distribution center to
business clients*/
float tca[ C ][ A ] = ...;/*transportation capacity from business clients to
collection center */
float tal[ A ][ L ] = ...;/* transportation capacity from collection center to
dismantling and remanufacturing center*/
```

```
float tlp[ L ][ P ] = ...;/* transportation capacity from dismantling and
remanufacturing center to potencial clients*/
float x = ...; /*weight of 50 masks


/*3-Decision Variables*/

dvar float+ SM[ S ][ M ][ R ];/* Flow of component r between supplier s and
Manufacturing center m (number of rolls) */
dvar float+ MW[ M ][ W ];/*Flow of masks between Manufacturing center m and
warehouse w (number of boxes) */
dvar float+ WD[ W ][ D ];/*Flow of masks between warehouse w and Distribution
center d (number of boxes) */
dvar float+ DC[ D ][ C ];/*Flow of masks between Distribution center d and
business client c (number of boxes) */
dvar float+ CC[ C ][ A ];/* Flow of used masks between business clients c and
collection center a (Kg) */
dvar float+ CR[ A ][ L ];/* Flow of used masks between collection center a and
dismantlimg and remanufacturing center l (Kg) */
dvar float+ RP[ L ][ P ][ V ];/*Flow of recycled materials between dismantlimg
and remanufacturing center l and potential client p (kg )*/
//dvar boolean Z[ L ];/*equals 1 IF the dismantling AND remanufacturing center l
is open at the begining of the planning horizon , 0 otherwise */
dvar boolean Y[ S ][ R ];/*equals 1 IF the supplier is selected at the begining
of the planning horizon , 0 otherwise */
//dvar boolean ZZ[ A ];/*equals 1 IF the collection center  l is open at the
begining of the planning horizon , 0 otherwise */
//dvar boolean ZM[ M ];/*equals 1 IF the manufacturing center  m is open at the
begining of the planning horizon , 0 otherwise */


dvar float+ Procurementcost;
dvar float+ Manufacturingcost;
dvar float+ Transportationcost;
dvar float+ Remanufacturingcost;
//dvar float+ Openmanufacturing;
//dvar float+ Openremanufacturing;
//dvar float+ Opencollectioncenter;
dvar float+ Selectionsupplier;
dvar float+ Sellmasks;
dvar float+ SellPP;
dvar float+ TOTALcost;
dvar float+ Revenues;
dvar float+ Cost;
dvar float+ Profit;
dvar float+ Totalprofit;


/*4-Objective function*/

maximize sum (l in L, p in P ,v in V: v==1)RP[ l ][ p ][ v ]*pp
//+ sum (l in L, p in P ,v in V: v==2)RP[ l ][ p ][ v ]*pp
//+ sum (l in L, p in P ,v in V: v==3)RP[ l ][ p ][ v ]*pp
```

```
+sum (d in D, c in C)DC[ d ][ c ]*pm/*Selling boxes(1 box=50 masks)to business
clients */


-sum(r in R,s in S,m in M) SM[ s ][ m ][ r ]*pc[ r ][ s ]/*Procurement cost*/
- sum(m in M,w in W) MW[ m ][ w ]* mc /*Manufacturing cost */
- sum(l in L,p in P,v in V:v==1) RP[ l ][ p ][ v ]*rc[ v ]/*Remanufacturing
costs*/
//- sum(m in M) ZM[ m ]*fc[ m ] /*Opening a new facility manufacturing  center
*/
//- sum(l in L) Z[ l ]*f[ l ] /*Opening a new facility rem center  */
//- sum(a in A) ZZ[ a ]*fff[ a ] /*Opening a new collection center  */
- sum(s in S,r in R) Y[ s ][ r ]*ff[ r ][ s ] /*Selecting a supplier  */



- sum(s in S,m in M,r in R) SM[ s ][ m ][ r ]*tcsm [ s ][ m ]*dsm[ s ][ m
]/*Transportation cost*/
- sum(m in M,w in W) MW[ m ][ w ]*tcmw [ m ][ w ]*dmw[ m ][ w ] - sum(w in W,d in
D) WD[ w ][ d ]*tcwd [ w ][ d ]*dwd[ w ][ d ]
- sum(d in D,c in C) DC[ d ][ c ]*tcdc [ d ][ c ]*ddc[ d ][ c ] - sum(c in C,a in
A) CC[ c ][ a ]*tcca [ c ][ a ]*dca[ c ][ a ]
- sum(a in A,l in L) CR[ a ][ l ]*tcal [ a ][ l ]*dal[ a ][ l ] ;
//+ sum(l in L,p in P,v in V) RP[ l ][ p ][ v ]*tclp [ l ][ p ]*dlp[ l ][ p ];



/*5-Constraints*/

subject to {


      forall(s in S,m in M,r in R)
          Constraint0:Procurementcost== sum(r in R,s in S,m in M) SM[ s ][ m ][ r
]*pc[ r ][ s ];/*Procurement cost*/

      forall(m in M,w in W)
          Constraint01:Manufacturingcost== sum(m in M,w in W) MW[ m ][ w ]*
mc;/*Manufacturing cost*/


      forall(r in R,s in S,m in M,w in W,d in D,c in C,a in A,l in L,p in P,v in
V)

          Constraint02:Transportationcost== sum(s in S,m in M,r in R) SM[ s ][ m
][ r ]*tcsm [ s ][ m ]*dsm[ s ][ m ]/*Transportation cost*/
      + sum(m in M,w in W) MW[ m ][ w ]*tcmw [ m ][ w ]*dmw[ m ][ w ] + sum(w in
W,d in D) WD[ w ][ d ]*tcwd [ w ][ d ]*dwd[ w ][ d ]
      + sum(d in D,c in C) DC[ d ][ c ]*tcdc [ d ][ c ]*ddc[ d ][ c ] + sum(c in
C,a in A) CC[ c ][ a ]*tcca [ c ][ a ]*dca[ c ][ a ]
      + sum(a in A,l in L) CR[ a ][ l ]*tcal [ a ][ l ]*dal[ a ][ l ];
```

```
      // + sum(l in L,p in P,v in V) RP[ l ][ p ][ v ]*tclp [ l ][ p ]*dlp[ l ][
p ];


      forall(l in L,p in P,v in V)
          Constraint03:Remanufacturingcost== sum(l in L,p in P,v in V:v==1) RP[ l
][ p ][ v ]*rc[ v ];/*Remanufacturing cost*/


      /*forall(m in M)
        Constraint04:Openmanufacturing==sum(m in M) ZM[ m ]*fc[ m
];/*Openmanufacturingcenter cost*/

      /*forall(l in L,p in P,v in V)
        Constraint05:Openremanufacturing==sum(l in L) Z[ l ]*f[ l ];/*Open
Remanufacturingcenter cost*/

      /*forall(a in A)
       Constraint06:Opencollectioncenter==sum(a in A) ZZ[ a ]*fff[ a ];/*Open
Collectioncenter cost*/

       forall(s in S,r in R)
        Constraint07:Selectionsupplier==sum(s in S,r in R) Y[ s ][ r ]*ff[ r ][ s
];/*Selection supplier cost*/


       forall(d in D, c in C)
         Constraint09:Sellmasks==sum (d in D, c in C)DC[ d ][ c ]*pm;/*Revenues
of selling mask */

       forall(l in L, p in P ,v in V)
        Constraint010:SellPP==sum (l in L, p in P ,v in V: v==1)RP[ l ][ p ][ v
]*pp;/*Revenues t of selling recycled components  */
        //+ sum (l in L, p in P ,v in V: v==2)RP[ l ][ p ][ v ]*pp
        //+ sum (l in L, p in P ,v in V: v==3)RP[ l ][ p ][ v ]*pp;

      forall(d in D,c in C,l in L,p in P,v in V)
         Constraint011:Revenues== sum (l in L, p in P ,v in V: v==1)RP[ l ][ p ][
v ]*pp/*Revenues joining selling mask and recycled components  */
      // + sum (l in L, p in P ,v in V: v==2)RP[ l ][ p ][ v ]*pp
      //  + sum (l in L, p in P ,v in V: v==3)RP[ l ][ p ][ v ]*pp
       +sum (d in D, c in C)DC[ d ][ c ]*pm;



    /*cost step by step*/

       forall(r in R,s in S,m in M,w in W,d in D,c in C,a in A,l in L,p in P,v in
V)

      Constraint012:Cost==sum(r in R,s in S,m in M) SM[ s ][ m ][ r ]*pc[ r ][ s
]/*Procurement cost*/
```

```
      + sum(m in M,w in W) MW[ m ][ w ]* mc /*Manufacturing cost */
      + sum(l in L,p in P,v in V:v==1) RP[ l ][ p ][ v ]*rc[ v ]/*Remanufacturing
costs*/
      //+ sum(l in L) Z[ l ]*f[ l ] /*Opening a new facility rem center  */
      + sum(s in S,r in R) Y[ s ][ r ]*ff[ r ][ s ] /*Selecting a supplier  */
      //+ sum(a in A) ZZ[ a ]*fff[ a ] /*Opening a new collection center  */
      //+ sum(m in M) ZM[ m ]*fc[ m ] /*Opening a new facility manufacturing
center  */

      + sum(s in S,m in M,r in R) SM[ s ][ m ][ r ]*tcsm [ s ][ m ]*dsm[ s ][ m
]/*Transportation cost*/
      + sum(m in M,w in W) MW[ m ][ w ]*(tcmw [ m ][ w ])*dmw[ m ][ w ] + sum(w
in W,d in D) WD[ w ][ d ]*tcwd [ w ][ d ]*dwd[ w ][ d ]
      + sum(d in D,c in C) DC[ d ][ c ]*(tcdc [ d ][ c ])*ddc[ d ][ c ] + sum(c
in C,a in A) CC[ c ][ a ]*tcca [ c ][ a ]*dca[ c ][ a ]
      + sum(a in A,l in L) CR[ a ][ l ]*(tcal [ a ][ l ])*dal[ a ][ l ];
      // + sum(l in L,p in P,v in V) RP[ l ][ p ][ v ]*tclp [ l ][ p ]*dlp[ l ][
p ];

       /*cost step by step with words*/

      forall(r in R,s in S,m in M,w in W,d in D,c in C,a in A,l in L,p in P,v in
V)
        Constraint0001:TOTALcost==
Procurementcost+Manufacturingcost+Transportationcost+Remanufacturingcost+Selectio
nsupplier;




       /*Profit =Revenues-Cost step by step*/

     forall(r in R,s in S,m in M,w in W,d in D,c in C,a in A,l in L,p in P,v in
V)

      Constraint013:Profit==sum (l in L, p in P ,v in V: v==1)RP[ l ][ p ][ v
]*pp+ sum (d in D, c in C)DC[ d ][ c ]*pm
      //+ sum (l in L, p in P ,v in V: v==2)RP[ l ][ p ][ v ]*pp
      //+ sum (l in L, p in P ,v in V: v==3)RP[ l ][ p ][ v ]*pp



      - sum(r in R,s in S,m in M) SM[ s ][ m ][ r ]*pc[ r ][ s ]/*Procurement
cost*/
      - sum(m in M,w in W) MW[ m ][ w ]* mc /*Manufacturing cost */
      - sum(l in L,p in P,v in V:v==1) RP[ l ][ p ][ v ]*rc[ v ]/*Remanufacturing
costs*/
      //- sum(l in L) Z[ l ]*f[ l ] /*Opening a new facility rem center  */
      - sum(s in S,r in R) Y[ s ][ r ]*ff[ r ][ s ] /*Selecting a supplier  */
      //- sum(a in A) ZZ[ a ]*fff[ a ] /*Opening a new collection center  */
      //- sum(m in M) ZM[ m ]*fc[ m ] /*Opening a new facility manufacturing
center  */
```

```
      - sum(s in S,m in M,r in R) SM[ s ][ m ][ r ]*tcsm [ s ][ m ]*dsm[ s ][ m
]/*Transportation cost*/
      - sum(m in M,w in W) MW[ m ][ w ]*tcmw [ m ][ w ]*dmw[ m ][ w ] - sum(w in
W,d in D) WD[ w ][ d ]*tcwd [ w ][ d ]*dwd[ w ][ d ]
      - sum(d in D,c in C) DC[ d ][ c ]*tcdc [ d ][ c ]*ddc[ d ][ c ] - sum(c in
C,a in A) CC[ c ][ a ]*tcca [ c ][ a ]*dca[ c ][ a ]
      - sum(a in A,l in L) CR[ a ][ l ]*tcal [ a ][ l ]*dal[ a ][ l ] ;
      //- sum(l in L,p in P,v in V) RP[ l ][ p ][ v ]*tclp [ l ][ p ]/dlp[ l ][ p
]*dlp[ l ][ p ];



/*Profit =Revenues-Cosst step by step with words*/

     forall(r in R,s in S,m in M,w in W,d in D,c in C,a in A,l in L,p in P,v in
V)

     Constraint014:Totalprofit==Sellmasks+SellPP-Procurementcost-
Manufacturingcost-Transportationcost-Remanufacturingcost-Selectionsupplier;



     forall(s in S,r in R )
             Constraint1: sum( m in M) SM[ s ][ m ][ r ]<= Y[ s ][ r ]*c[ r ][ s
] ;/* Respect supplier capacity and selection of supplier  */


     forall( c in C )
             Constraint2: sum( d in D) DC[ d ][ c ] == d[ c ];/*For each client,
the demand must be satisfied  */

     forall( c in C)
             Constraint3:sum(a in A)CC[ c ][ a ]== sum( d in D) DC[ d ][ c ]*
alpha[ c ]*x; /*  For each client, the amount of returned product is a % of the
quantity of  products received  */

     forall (m in M )
             Constraint4: sum( w in W) MW[ m ][ w ]<=  q[ m ] ;/* For each plant
production capacities of manufacturing center m must be respected */

    forall(l in L )
             Constraint5: sum( a in A) CR[ a ][ l ]<= k[ l ] ;/* BINARY good open
facility—Capacity of dismantling and remanufacturing center */

    forall(a in A )
             Constraint6: sum( c in C) CC[ c ][ a ]<= kk[ a ] ;/* BINARY good
open facility—Capacity of dismantling and remanufacturing center */

    forall( m in M,r in R)
             Constraint7: sum( s in S) SM[ s ][ m ][ r ] == h[ r ]* sum(w in
W)MW[ m ][ w ] ;/*Demands of manufacturing centers for raw materials must be
respected (for each plant and raw material)  */
```

```
    forall( w in W)
             Constraint8: sum( m in M) MW[ m ][ w ] ==  sum(d in D)WD[ w ][ d ]
;/*The inflow of a warehouse does not exceed the total flows sent from
Manufacturing centers m to the warehouse */

    forall( l in L,v in V)
             Constraint9: sum( a in A) CR[ a ][ l ]*hh[ v ] ==  sum(p in P)RP[ l
][ p ] [ v ]*x;/* The flow between Rem center and potential clients is a % of the
amount of recycled component v present in the total number of mask collected  */

    forall(a in A )
             Constraint10: sum( c in C) CC[ c ][ a ]== sum( l in L) CR[ a ][ l ]
; /*All mask collected at the collection centers must be transported to
remanufacturing centers */


    forall(d in D )
             Constraint11: sum( w in W) WD[ w ][ d ]== sum( c in C) DC[ d ][ c ]
; /* The inflow of a Dc does not exceed the total flows sent from warehouse to DC
*/


 //Transportation Constraints

      forall( s in S,m in M,r in R)
        Constraint12:  SM[ s ][ m ][ r ] <= tsm[ s ][ m ] ;/*Transportation
capacity from manufacturing center to warehouse  */

      forall( w in W,m in M)
        Constraint13:  MW[ m ][ w ] <= tmw[ m ][ w ] ;/*Transportation capacity
from manufacturing center to warehouse  */

      forall( w in W,d in D)
             Constraint14:  WD[ w ][ d] <= twd[ w ][ d ] ;/*Transportation
capacity from warehouse to distribution center  */

      forall( d in D,c in C)
             Constraint15:  DC[ d ][ c ] <= tdc[ d ][ c ] ;/*Transportation
capacity from DC to business clients  */

      forall( c in C,a in A)
             Constraint16:  CC[ c ][ a ] <= tca[ c ][ a ];/* Transportation
capacity from business clients to collection center */

      forall( a in A,l in L)
             Constraint17: CR[ a ][ l ] <= tal[ a ][ l ];/* Transportation
capacity from Collection center to dismantling and remanufacturing center */

      /*forall( l in L,p in P,v in V)
             Constraint18: RP[ l ][ p ][ v ] <= tlp[ l ][ p ];/* Transportation
capacity from  dismantling and remanufacturing center to potential clients */
}
```

```
execute
{
var file=new IloOplOutputFile("export.csv");
file.writeln("Objective value = ", cplex.getObjValue());

          file.writeln("Procurementcost =
",",",",Procurementcost.solutionValue,",");
          file.writeln("Manufacturingcost =
",",",",Manufacturingcost.solutionValue,",");
          file.writeln("Transportationcost =
",",",",Transportationcost.solutionValue,",");
          file.writeln("Remanufacturingcost =
",",",",Remanufacturingcost.solutionValue,",");
         // file.writeln("Openmanfacturing =
",",",",Openmanufacturing.solutionValue,",");
         //file.writeln("Openremanufacturing =
",",",",Openremanufacturing.solutionValue,",");
         //file.writeln("Opencollectioncenter =
",",",",Opencollectioncenter.solutionValue,",");
          file.writeln("Selectionsupplier =
",",",",Selectionsupplier.solutionValue,",");
          file.writeln("Sellmasks = ",",",",Sellmasks.solutionValue,",");
          file.writeln("SellPP = ",",",",SellPP.solutionValue,",");
          file.writeln("Revenues = ",",",",Revenues.solutionValue,",");
          file.writeln("Cost = ",",",",Cost.solutionValue,",");
          file.writeln("TOTALcost = ",",",",TOTALcost.solutionValue,",");
          file.writeln("Profit = ",",",",Profit.solutionValue,",");
          file.writeln("Totalprofit = ",",",",Totalprofit.solutionValue,",");
}
```

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