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Economic feasibility analysis of a medical mask closed-loop supply chain: a Canadian case study

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***Abstract* – The world is being exposed to a global health crisis due to covid-19. This situation is generating an unprecedented increase in the use of single-use medical materials, notably procedural facemasks. This study focuses on the design and planning of a closed-loop supply chain (SC) for dealing with end-of-life procedural facemasks. An optimization model to efficiently collect and recycle used procedural facemasks is proposed. The main benefits are the correct disposal of contaminated products and component recycling. The considered SC network includes virgin raw material, suppliers, facemask manufacturing centers, warehouses, distribution centers, business clients, collection centers, dismantling and recycling centers, and finally, clients for the recycled components. Decisions to be made include material flows in the network, supplier and facility (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. Various scenarios are analyzed to identify the conditions under which the SC is profitable.**

***Keywords* – Single-use medical materials, procedural facemasks, Reverse Logistics, Closed-loop supply chain, Recycling, Circular economy.**

1 INTRODUCTION

The world is being exposed to a global health crisis since 2019 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. The government of Canada in all Canadian provinces implemented sanitary measures to combat the coronavirus including individual protective equipment such as facemasks in our 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 protective equipment manufacturing and supply during the pandemic. Among these agreements was the production of 157 million masks by all Canadian facemask 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 masks and, therefore, as a global effect, some masks ended up on coasts or beaches and water environments as a waste at the term of their effective life [Ardusso et al., 2021; Xu & Ren, 2021]. This situation could be a risk for humans and the environment if the waste is not handled properly [Sarkodie & Owusu, 2021].

Therefore, there is a need to develop strategies to efficiently collect masks at the end of their life. From the logistics perspective, this can be addressed by establishing reverse logistics networks or closed-loop supply chains (SCs) and determining most efficient "paths" for end-of-life products collection and recovery such as recycling to favor value creation from what would otherwise be considered as a contaminated pollutant. This is an example of how circular economy could be implemented in practice [Korhonen et al., 2018; Liu & Ramakrishna, 2021; Prieto-Sandoval et al., 2018]. First, this study analyzes existing literature on reverse logistics and closed-loop SC design and planning in the medical sector. Second, it proposes a Mixed Integer Linear Programming Model (MILP) to design a closed-loop SC for collecting and recycling used procedural facemasks. The SC considered includes virgin raw materials, suppliers, facemask manufacturing centers, warehouses, distribution centers, business clients, collection centers, dismantling/recycling centers, and finally, clients for the recycled components. Decisions to be made include material flows in the network, and supplier 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. Various scenarios are analyzed to identify the conditions under which the SC is profitable. Therefore, this work contributes to address the important problem of efficient collection and recycling of facemasks. The remainder of the paper is as follows: Section 2 presents our literature review. Section 3 presents the developed mathematical model; Section 4 describes and discusses our results. Finally, Section 5 presents our main conclusions and research perspectives.

2 LITERATURE REVIEW

Various SC structures such as forward, reverse, and closed-loop SCs serve different purposes. The last two structures allow the collection of products at the end of their useful life and favor meeting circular economy objectives as proposed, for example, by Recyc-Québec [Recyc-Québec, 2019]. The first objective is to manufacture and consume more consciously products to use fewer resources and protect the ecosystem. A second objective is to optimize the resources that have already been used, extending their life or giving them a new one.

Forward logistics or forward SCs aim to gradually transform raw materials into manufactured products to satisfy customers' demand [Fleischmann et al., 1997]. Reverse logistics refer 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 [Recyc-Québec, 2019]. The integration of forward and reverse logistics results in closed-loop SCs [Kumar & Kumar, 2013]. We can further distinguish open-loop SCs; end-of-life products are not collected by the original manufacturer but by an independent manufacturer [Doctori-Blass & Geyer, 2009], and closed-loop SCs; end-of-life products are collected by the original manufacturer or by another company playing a role in the manufacturer's SC [Chouinard, 2003].

[Shi, 2009] designed a closed-loop SC 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 discusses 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 technology in a closed-loop SC 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 closed-loop SC, and there was a saving of $140 per day. [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 in a long duration. 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. 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 open-loop SC 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, Paydar, et al., 2020] proposed a robust possibilistic programming model for designing an open-loop SC 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 open-loop SC for the disposable of healthcare supplies such as dressing set, peripheral venous catheter (PVC), 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 (in Iran) focused on 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, Pourmehdi, et al., 2020] which is based on [Kargar, Paydar, 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 open-loop SC mathematical model to support decision-making regarding the location of temporary facilities to have enough space to handle the most significant volume of medical waste and avoid its accumulation over long periods, and transportation planning. 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]. [Setiawan et al., 2021] proposed a closed-loop SC model encompassing three objectives. The first one maximizes profit, by considering the quantity of 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 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 closed-loop SC 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.

3 PROBLEM DESCRIPTION AND MATHEMATICAL MODEL FORMULATION

3.1 Problem description

Our study focuses on a closed-loop SC that generates its revenues from selling procedural facemasks and recycled components (e.g., polypropylene) from used facemasks. In other words, the facemask 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 masks, manufacturing centers (the manufacturing process is shown in figure 1), warehouses, distribution centers, business clients (forward SC), collection centers, dismantling and recycling centers and clients for the recycled components (reverse SC). The recycling process consists in dismantling and separating the three components of the 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.

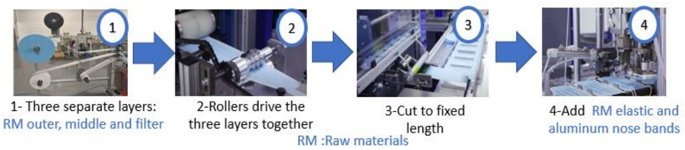

Figure 1. Manufacturing process of facemasks

The problem consists in determining the efficient strategy for the collection and recycling of facemasks 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 7), 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.

To build a realistic case study, we collaborated with different companies in the Montreal region and in the province of Québec, involved in mask manufacturing, raw material supply, mask distribution, used mask collection, procedural mask and polypropylene users (clients of masks and polypropylene, respectively). The mask manufacturer has established its manufacturing, warehouse, and distribution centers in Montreal Island. We are interested in studying different configurations (cases) of the used mask reverse logistics networks such as a closed-loop SC, where the manufacturing company carries out the collection and recycling process itself or a reverse logistics network under the responsibility of a distinct company that would operate independently or in collaboration with the manufacturing company. This study analyzes the profitability of each configuration. To this end, we defined five different cases as shown in Table 1.

Table 1. Proposed closed-loop SC scenarios

CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
CC=RC=MC Same location CLSC	CC=RC Same location CLSC	CC=W; RC=MC Same location CLSC	CC=W Same location CLSC	CC=RC Same location RL

CC: collection center W: warehouse
MC: manufacturing center CLSC: closed-loop SC
RC: remanufacturing center RL: reverse logistics

The first four cases present closed-loop SCs 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 2. 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 masks and produce/sell polypropylene pellets.

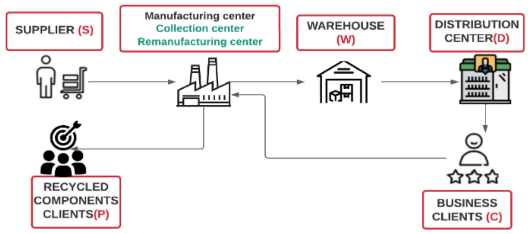

Figure 2. The closed-loop SC configuration in case 1

The second case considers to locate the collection and recycling centers in the same (new) facility, as shown in figure 3. 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 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 facility as shown in figure 4. 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.

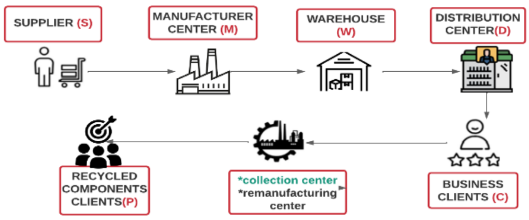

Figure 3. The closed-loop SC configuration in case 2

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

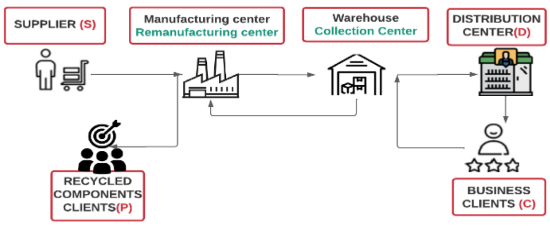

Figure 4. The closed-loop SC configuration in case 3

The fourth case considers locating the collection center and the warehouse in the same facility (existing warehouse) and having a new facility for the recycling center, as shown in figure 5. Investments in case 4 include the costs of the warehouse size extension, and technology, machinery, and human resources investments needed for the collection center

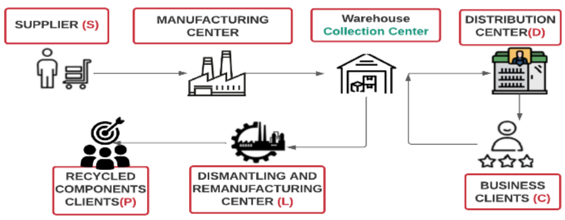

Figure 5. Closed-loop SC configuration in case 4

Finally, case 5 (figure 6) is based on a reverse logistics network configuration, where the business clients of masks (cases 1 to 4) are now the suppliers of raw materials (used masks) for the collection and recycling centers (both located in the same new facility to establish). This case encompasses two, sub-cases, case 5.1 where only polypropylene is recycled and case 5.2 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 masks and manufacturing polypropylene pellets and aluminum.

Figure 6. The reverse logistics network 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) facemasks. All other parameters remain fixed (see Table 2).

Table 2. 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 masks per scenario		
80%	50 %	25%
Scenario 1,4,7,10,13	2,5,8,11,14	3,6,9,12,15

* This parameter is not considered in case 5.
** In case 5.2, 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
- Elastic and aluminum components are not recycled in case 1 to case 4, and in case 5.1.
- Elastic component is not recycled in cases 5.2
- The planning horizon duration is one year
- The location of facilities (warehouse, manufacturing, and distribution centers) is predetermined. The location of the other two facilities (collection and recycling centers) are determined based on the results of the different SC configuration cases (based on the return on investment (ROI) indicator). The best configuration would indicate the location

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 sets, indices, parameters, decision variables, objective function and constraints are as follows:

- 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.

- Decision Variables

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

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

- Parameters

PC_{rs} Procurement cost of 1 unit of component r from supplier s (1 unit =1 roll)
MC Manufacturing cost of 1 unit of mask (1unit =1box =50 masks)
RC_v Remanufacturing cost of 1 unit of recycled component v (1 unit =1 Kg)
C_{sr} Shipping capacity of supplier s for component r
D_c Mask demand (in number of boxes) of business client c
$\propto_c$ % of returned masks by business client c
Q_m Capacity of manufacturing center m (boxes)
K_l Capacity of recycling center l (kg)
KK_a Capacity of collection center a (kg)
H_r The amount of component r required to produce 1 unit of masks
HH_v The amount of recycled component v present in 1 kg of masks
P_m Selling price for 1 unit of masks (1 box)
PP Selling price of recycled components
$TCIJ_{ij}$ Transportation cost of 1 unit of masks per km between origin facility i and destination facility j
DIJ_{ij} Distance in km between origin facility i and destination facility j
TIJ_{ij} Transportation capacity between origin facility i and destination facility j (number of containers)
FF_{rs} Fixed cost to select a supplier s
x Conversion factor (0.154 kg=1 box of 50 masks)

- Objective Function (1)

Maximize

$$\sum_{d\in D}\sum_{c\in C}(DC_{dc} * PM)$$
$$+\sum_{l\in L}\sum_{p\in P}\sum_{v\in V}\left(RP_{lpv} * PP\right)$$
$$-\sum_{r\in R}\sum_{s\in S}\sum_{m\in M}(SM_{smr} * PC_{rs})$$
$$-\sum_{m\in M}\sum_{w\in W}(MW_{mw} * MC)$$
$$-\sum_{s\in S}\sum_{m\in M}\sum_{r\in R}(SM_{smr} * TCSM_{sm} * DSM_{sm})$$
$$-\sum_{m\in M}\sum_{w\in W}(MW_{mw} * TCMW_{mw} * DMW_{mw})$$
$$-\sum_{w\in W}\sum_{d\in D}(WD_{wd} * TCWD_{wd} * DWD_{wd})$$
$$-\sum_{d\in D}\sum_{c\in C}(DC_{dc} * TCDC_{dc} * DDC_{dc})$$
$$-\sum_{c\in C}\sum_{a\in A}(CC_{ca} * TCCA_{ca} * DCA_{ca})$$
$$-\sum_{a\in A}\sum_{l\in L}(CR_{al} * TCAl_{al} * DAL_{al})$$
$$-\sum_{l\in L}\sum_{p\in P}\sum_{\substack{v\in V\\ v=1}}\left(RC_v * RPL_{pv}\right)$$
$$-\sum_{S}\sum_{R}(Y_{sr} * FF_{rs})$$

- Constraints

$$\sum_{m\in M} SM_{smr} \leq Y_{sr} * C_{sr} \qquad \forall s,r \tag{2}$$
$$\sum_{d\in D} DC_{dc} = D_C \qquad \forall c \tag{3}$$
$$\sum_{a\in A} CC_a = \sum_{d\in D} DC_{dc} * alpha_c * X \quad \forall c \tag{4}$$
$$\sum_{w\in W} MW_{mw} \leq q_m \qquad \forall \mathrm{m} \tag{5}$$
$$\sum_{c\in C} CC_{ca} \leq KK_a \qquad \forall \mathrm{a} \tag{6}$$
$$\sum_{a\in A} CR_{al} \leq K_l \qquad \forall l \tag{7}$$
$$\sum_{s\in S} SM_{smr} = \sum_{w\in W} MW_{mw} * H_r \qquad \forall \mathrm{r,m} \tag{8}$$
$$\sum_{m\in M} MW_{mw} = \sum_{d\in D} WD_{wd} \qquad \forall w \tag{9}$$
$$\sum_{a\in A} CR_{al} * HH_v = \sum_{p\in P} RP_{lpv} * \mathrm{X} \qquad \forall\, l,v \tag{10}$$
$$\sum_{c\in C} CC_a = \sum_{l\in L} CR_{al} \qquad \forall a \tag{11}$$
$$\sum_{w\in W} WD_{wd} = \sum_{c\in C} DC_{dc} \qquad \forall d \tag{12}$$
$$SM_{smr} \leq TSM_{sm} \qquad \forall m,w \tag{13}$$
$$MW_{mw} \leq TMW_{mw} \qquad \forall m,w \tag{14}$$
$$WD_{wd} \leq TWD_{wd} \qquad \forall d,w \tag{15}$$
$$DC_{dc} \leq TDC_{dc} \qquad \forall d,c \tag{16}$$
$$CC_{ca} \leq TCA_{ca} \qquad \forall a,c \tag{17}$$
$$CR_{al} \leq TAL_{al} \qquad \forall a,l \tag{18}$$
$$\mathrm{SM_{smr}, MW_{mw}, WD_{wd}, DC_{dc}, CC_{ca}, CR_{al}, RP_{lpv}} \geq 0 \tag{19}$$
$$Y_{sr}\ \{0,1\} \tag{20}$$

The objective function (1) maximizes the total profit of the SC that includes total revenues (generated from selling masks and recycled components) minus total costs (procurement, manufacturing, transportation recycling, and supplier selection costs).

Constraints (2) ensure the respect of the suppliers' capacity. Constraints (3) indicate that the demand for masks must be satisfied for each client. Constraints (4) restrict for each client the amount of collected used masks (expressed in % of the quantity of masks received). Constraints (5) ensure the respect of the production capacity of the manufacturing centers. Constraints (6) ensure the respect of the collection centers' capacity. Constraints (7) assure the respect of the recycling centers' capacity. Constraints (8) guarantee that demands of manufacturing centers for raw materials are respected (for each facility and raw material type). Constraints (9) indicate that the inflow of a warehouse does not exceed the total flows sent from the manufacturing centers to that warehouse. Constraints (10) indicate that the amount of recycled components (sold to clients) is equal to the amount recovered from collected masks. Constraint (11) indicate that all masks collected at the collection centers must be transported to the recycling centers. Constraints (12) assure that the flows between the warehouses and the distribution centers are the same from distribution center to business clients (flow balance constraints). Constraints (13-18) ensures that the flows between the facilities do not exceed the transportation capacity. Finally, constraint (19) ensures that the decision variables are positive and continuous, and constraints (20) that the decision variables are binary.

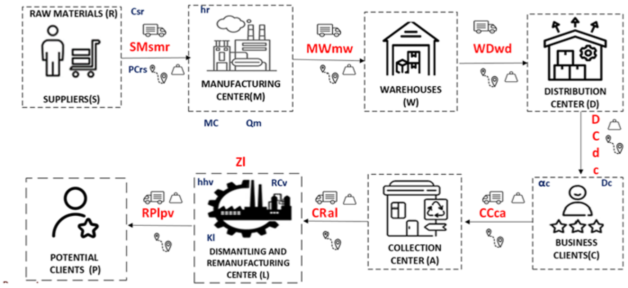

Figure 7. Medical facemask closed-loop SC configuration and planning problem formulated as a MILP

We used this model for cases 1 to 4 and specifically for case 5 we keep just the reverse logistics part starting from business clients to potential clients (as shown in figure 6).

4 RESULTS

To solve the mathematical model, first, we performed a rigorous data collection. This was supported by four industrial companies, who provided us with quantitative and geographic data. The problem was solved by using IBM ILOG CPLEX on a lap-top with the processor Intel i5-1035G1 and a RAM capacity of 12 Gb. As we mentioned in Section 3, three different scenarios within each case (1 to 5) are analyzed based on the parameters presented in Table 1 (15 scenarios in total). Our aim is to evaluate which scenarios and cases yield the highest profits and best ROIs (return on investment). ROI (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). The investments are estimated based on the fixed costs required to open a new facility or extending an existing one (see Section 3.1). These investments are not included as costs in the mathematical model. The results of cases 1, 2, 3, 4, and 5 are shown in Table 3, 4, 5, 6, and 7, respectively. In addition, 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, it is essential to determine how varying the investment values would impact the SC profitability. The results of cases 1 (scenario 1), 2 (scenario 4), 3 (scenario 7), 4 (scenario 10), and 5 (scenario 14) are shown in figures 8, 9, 10, 11, and 12 respectively.

Table 3. Results of case 1 (scenarios 1, 2, and 3)

% of returned (used) masks	80	50	25
Scenario	# 1	# 2	# 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 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**

For case 1 (Table 3), the results show that all scenarios are profitable. The percentage of returned 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 5.1). Otherwise, the profit and ROI would be slightly higher (this aspect is analyzed in case 5.2). Scenario 1 is the best with a ROI of 55.28%. The sensitivity analysis (see Figure 8) shows that even in the worst case, we obtain a good ROI (27,64%).

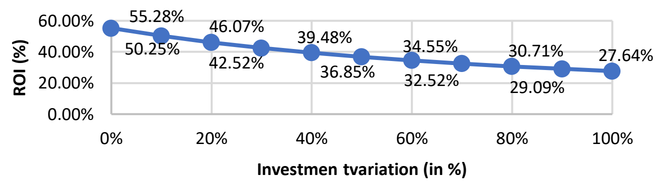

Figure 8. Results of the sensitivity analysis (Case 1, scenario 1)

Table 4. Results of case 2 (scenarios 4, 5, and 6)

% of returned masks	80	50	25
Scenario	# 4	# 5	# 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 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 ($)	12,188,327.4	12,113,204.6	12,050,602.3
Total profit ($)	5,992,118.42	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 shows that all scenarios within case 2 are profitable. The best scenario, in this case is scenario 4, with an ROI of 42.80%. Our sensitivity analysis (Figure 9) reveals that even in the worst case, we continue to obtain a good value of the ROI (21,40%).

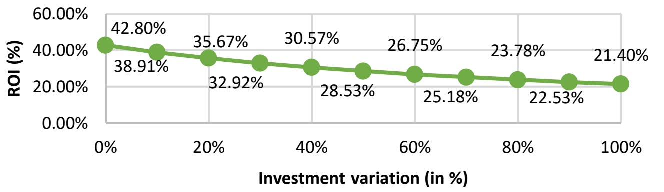

Figure 9. Results of the sensitivity analysis (Case 2, scenario 4)

All scenarios of case 3 are profitable (Table 5). The best scenario is #7, with an ROI of 56.21%.

Table 5. Results of case 3 (scenarios 7, 8, and 9)

% of returned masks	80	50	25
Scenario	# 7	# 8	# 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 ($)	600	600	600
Total cost	6,202,362.20	6,136,653.23	6,081,895.76
Revenues from selling masks ($)	11,988,000	11,988,000	11,988,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total revenue ($)	12,188,327.7	12,113,204.6	12,050,602.3
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**

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

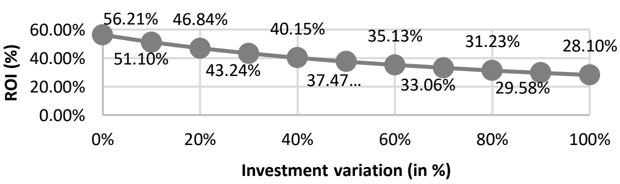

Figure 10. Results of the sensitivity analysis (Case 3, scenario 7)

Table 6 shows that all scenarios in case 4 are profitable. The best scenario, in this case, is scenario 10, with an ROI of 49.88%.

Table 6. Results of case 4 (scenarios 10, 11, and 12)

% of returned masks	80	50	25
Scenario	# 10	# 11	# 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 ($)	231,353.53	226,738.15	231,353.53
Remanufacturing cost ($)	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 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 (%)	**49.88**	**49.80**	**49.74**

Again, we observe that we continue to have a rather good ROI even in the worst case (22.17%) (see Figure 11).

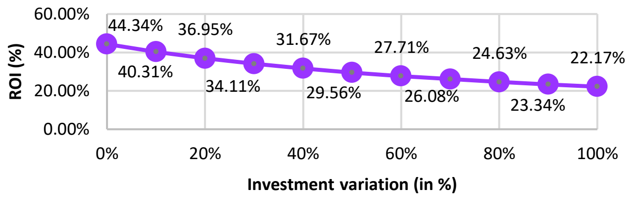

Figure 11. Results of the sensitivity analysis (Case 4, scenario 10)

For case 5.1, the revenue generated from selling polypropylene lead to a positive profit (Table 7). 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 8). The purpose of including aluminum is to assess how it would impact the SC profitability.

Table 7. Results of cases 5.1 (scenarios 13, 14, and 15)

% of returned masks	80	50	25
Scenario	#13	#14	#15
Transportation cost ($)	6,153.84	3846.15	1,923.075
Remanufacturing cost ($)	162,916.92	101,823.08	50,911.54
Total cost ($)	169,070.76	105,669.23	52,834.61
Total investment ($)	4,000,000	4,000,000	4,000,000
Revenues from selling polypropylene ($)	200,327.47	125,204.67	62,602.34
Total revenue ($)	200,327.47	125,204.67	62,602.34
Total profit ($)	31,256.71	19,535.44	9,767.73
ROI (%)	**0.78%**	**0.48%**	**0.24%**

Table 8. Results of case 5.2 (scenarios 16, 17, and 18)

Scenario	#16	#17	#18
Revenues from selling aluminum ($)	3,356.64	2,907.90	1,048.95
Total revenue ($)	203,684.11	127,302.57	63,651.29
Total profit ($)	34,613.35	21,633.35	10,816.67.
ROI (%)	**0.86%**	**0.54%**	**$0.27%**

Cases 5.1 and 5.2 lead to very low profits and ROIs even in the best scenario (#16; ROI = 0.86%). This means that it is not profitable to establish a reverse logistics network without

integrating it with the forward logistics. To address this situation, the investment should be lower, for example by obtaining a governmental subsidy. Our sensitivity analysis on the investment (see Figure 12) shows that the ROI could increase up to 4.33% if the investment is lower than the initial value by 80%.

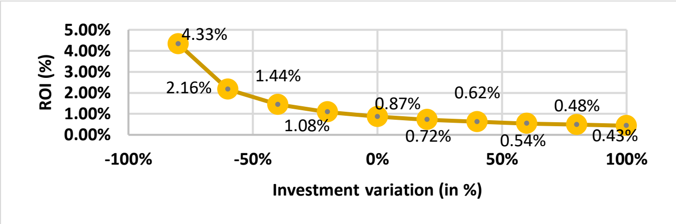

Figure 12. Results of the sensitivity analysis (Case 5.2, scenario 16)

Overall, the best profit and ROI are obtained in case 3 and scenario 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 masks is collected. The ROI in this scenario is 56.21%. Therefore, the most profitable SC configuration is a closed-loop one. The revenues result mainly from selling masks. The results in cases 5.1 and 5.2 reveal that it is not reasonable to establish a reverse logistics network for collecting and recycling used masks without integrating it with the forward SC or decreasing the investment required for mask collection and recycling. This latter could be possible if a substantial governmental subsidy is granted. Another element that improves profitability is sharing existing facilities (warehouse and manufacturing centers) for collecting and recycling the used masks, since this decreases the investments.

5 CONCLUSIONS

This study provides decision-makers with the best logistics conditions under which the SC of recycled masks is profitable. Our scenarios consider five different configurations of the SC (closed-loop and reverse logistics network), three different rates of returned masks, and two recycled components (polypropylene and aluminum). A realistic case study in the Montreal region was used to perform our analysis and derive our conclusions. The results show that it is not reasonable to establish a reverse logistics network for collecting and recycling 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 masks. 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 masks, by considering different parameters, constraints, and scenarios. The model could be also adapted for other products. As a future research direction, it is suggested 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 masks and quantity of used masks that could be collected).

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