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Optimization of production batches in a circular supply chain under uncertainty

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Abstract: During the covid-19 outbreak, millions of people are required to use disposable masks to protect themselves from this infectious disease. Under an exponential spread tendency of this pandemic, the conventional end of life of these plastic products is to dispose of them in landfills or to incinerate them. Actually, this scenario is the most optimistic one since millions of tonnes of masks are ended up in oceans. Therefore, recycling which is one of the circular economy concepts remains the key solution aiding countries to mitigate masks pollution, in addition to its role in decreasing the widespread of the disease. In this paper, we will examine several studies dealing with reverse logistics and circular economy, then we will develop a closed-loop supply chain design during the pandemic and translate it mathematically as a MILP model under certain and uncertain client demand. Finally, the problem will be solved using IBM ILOG Cplex Optimization Studio and the obtained results will be discussed.

Keywords: management of medical waste, disposable masks, circular economy, MILP, IBM ILOG Cplex Optimization Studio.

1. INTRODUCTION

Medical waste, especially protective devices (masks) have increased since the coronavirus outbreak, around 129 billion of disposable masks (plastic product) are used every month, Prata et al.,2020, which is a ubiquitous problem added to the plastic waste management challenges. Countries struggle to collect the maximum of used masks and dispose of them in landfills or incinerate them but this effort remains not enough to tackle the important and fast increase of masks waste during the pandemic.

Hence, decision-makers need to establish ecological and efficient strategies to manage disposable masks waste. We can only achieve this by following a circular economy and getting rid of the take-make-waste mentality. Therefore, a convenient design of a reverse supply chain for disposable masks is highly recommended to mitigate medical waste and help decrease the spread of this infectious disease. The key process to succeed in our target is recycling which is the action of returning the used product to the production center to remanufacture it. In this regard, we kept it in a closed-loop so, we helped decrease the production of other masks from crude materials plus, the important role of mitigating pollution.

In practice, it is in Châtellerault, France, where the first initiative of recycling masks has begun, thanks to a small eco-friendly start-up named plaxtil. Since the coronavirus outbreak until June 2020, this company has succeeded to remanufacture about 50000 masks according to its co-founder Olivier Civil. Recycled products are used as rulers for students, or other plastic products (no available information about recycling masks into other masks). Thus, a proper design of a closed-loop supply chain is of paramount significance under unclear pandemic conditions.

In this paper, we tried to optimize a reverse supply chain design for disposable masks under certain and uncertain conditions.

This work is organized as follows: The next section is a literature review in which we will give some well-known definitions of the circular economy then we will indicate some studies dealing with reverse logistics. Finally, we will propose a closed-loop supply chain design with the related mixed-integer linear programming “MILP”, and we will use IBM ILOG Cplex Optimization Studio to solve the problem, discuss the provided results and the outlook of the study.

2. LITERATURE REVIEW

We review the related literature under 2 groups: First, we will present some definitions of the circular economy concept, in the second part, we will cover a set of studies which have planted reverse logistics supply chains.

2.1 Circular economy

Considering it as the potential solution of the climate change problem, this concept has gained a lot of attention around the world. According to Geissdoerfer et al.,2017, the Circular Economy CE is “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops.” Ekins et al.,2019, confirm that the CE “is one that has low environmental impacts and makes good use of natural resources through high resource efficiency and waste prevention, especially in the manufacturing sector, and minimal end-of-life disposal of materials”.

The most known definition is the one given by Ellen MacArthur Foundation (charity organization), which considers CE as “an industrial system that restorative or regenerative by intention and design. For EMF circular economy is the best alternative to traditional linear economy (make, use, dispose)”.

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2.2 Reverse logistics studies

For the first study, Li et al., 2017 investigated the coordination strategies among different parties in a three-echelon reverse supply chain compounds of single collector, single remanufacturer and two retailers, through this study they considered 4 mathematical models: the completely decentralized model (M1), the remanufacturer and retailer cooperative model (M2), the remanufacturer and the collector cooperative model (M3), and the completely centralized model (M4). Numerical analyses were done to compare the models and resulted showed that a centralized model is the most efficient model to maximize economic and social benefit. In another study, Heydari et al., 2018 considered a reverse supply chain under stochastic remanufacturing capacity, in the paper authors modeled 3 scenarios: centralized, decentralized and sharing revenue model, the third one is developed in which the manufacturer shares revenue selling refurbished items with the retailer. Numerical results and sensitivity analyses prove that the proposed revenue sharing mechanism not only improves the economic performance of each supply chain SC member but also creates a Pareto improving situation in which both members gain more profit.

Plastic waste is a target material in managing a sustainable supply chain, in this subject, Mohammadi A.S., et al., 2018, examined a multi-objective, multi-stage, multi-product model to design a sustainable closed-loop plastic supply chain network design “SCND”, with financial considerations, a multi-stage stochastic approach and mixed integer linear programming approach were implemented to cope uncertainty issue. Objectives of this model were: maximizing total revenue, maximizing social benefit and it was solved by path formulation and augmented epsilon-constraint methods. A plastic company data has been utilized as a study case to assess the applicability of the model, and computational results indicate that considering financial decisions increase the service level and the objective functions besides, Relative Value of Multi-Stage Stochastic Approach “RVMSA” index showed that stochastic approach have better outcomes in comparison with the deterministic one.

In our sanitary conditions, we notice that a circular economy, where recycling is a major process, is still scarce in paper, and also in real-life, we can explain this by the difficulty of managing hazardous waste, that’s why management of infectious medical waste is limited to landfills disposal or incineration. For example, Yu et al., 2020, studied the reverse logistics network design of medical waste in Wuhan, China during coronavirus outbreak. Using a multi-objective, multi-period mixed integer programming model, to improve the location decisions of temporary facilities and the operational planning. In order to solve the multi-objective optimization problem and generate Pareto solutions Authors in this paper used an interactive fuzzy approach, besides, a real-world case study based on the covid-19 outbreak in Wuhan was used to prove the model efficiency. Results suggest to install a temporary incinerator to cope with the tremendous increase of medical waste and to face the risk of contamination. For Kargar et al., 2020, they designed an infectious medical waste reverse logistics model (fig1). In this study authors developed a linear programming model with 3 objectives to minimize the total cost, the risk associated with the transportation and the treatment of infectious medical waste, and the maximum amount of uncollected waste generation centers. This Multi-objective model is solved by the Revised Multi-Choice Goal Programming method “RMCGP”, the validity of the model was examined using a real case from Iran, and the final results showed that the model created a balance between the three considered objectives.

Govindan k. et al., 2021, proposed a bi-objective mixed integer linear programming model for infectious and non-infectious medical waste during covid-19 outbreak, their model can minimize the total costs and the risk of the population exposure to pollution. To solve this model, a fuzzy goal programming approach was used. Results of this proposed model can help decision-makers to adopt a suitable scenario that could decrease the risk on budget.

Another bi-objective mixed integer linear programming was suggested by Babaei T. et al., 2021, in order to solve vehicle routing problem transportation planning and outsourcing of hazardous medical waste management in a pandemic outbreak and with sustainable goals, this work aim to minimize the total cost with respect to the travelling costs, vehicles usage costs, outsourcing costs and pollution costs, the second goal is to minimize the risk of infection during collecting, transportation and disposal. Considering the real-world assumptions, they validated their model using Gams/Cplex solver, compare different conditions and discuss the practical implications using the sensitivity analysis of demand parameter.

Bibliographic data are really scarce when talking about closed-loop supply chain of medical waste (specially masks) during this pandemic, we can only name Setiawan et al., 2021, who have designed a closed-loop supply chain network for different types of masks. Members of the proposed supply chain were: suppliers, manufactures, distributors and retailers in the forward flow and collection centers, separate centers, recycling centers, recycling centers, and disposal centers in the reverse flow. Authors, in this regard, developed a multi-objective, mixed integer linear mathematical model where objectives were: increasing the total profit, mitigating the total environment impact, and maximizing social responsibility. To solve and optimize the mathematical model, a fuzzy optimization approach in Gams software was used.

3. MATHEMATICAL MODELING OF A CLOSED-LOOP SUPPLY CHAIN FOR DISPOSABLE MASKS

3.1 Methodology

![Figure 1: Closed-loop supply chain design for disposable masks.](image-url)
In this section, we will develop a closed-loop supply chain design model for disposable masks under covid-19 outbreak (Fig.1). The chain as shown in the scheme above begins with the distribution center which delivers a number of masks (client demand) to hospitals (customer center) then a number of used masks will return from hospitals to the manufacture/remanufacture center where they will be treated (anti-covid treatment) then recycled to produce other masks, and finally transported to the storage center to be distributed again to hospitals. The process's waste will be bought by another another factory to produce rulers or other plastic products.

The main target of this reverse logistic design is to minimize recycling costs as much as mitigating masks waste. The model is assumed as single-objective, multi-period, multi-level, and single product mode. A mixed integer linear programming problem is developed and solved by the software IBM ILOG Cplex Optimization Studio. Transport, manufacture/remanufacture, and storage costs are supposed to be certain, as well as centers capacities. The customer demand “D” is considered as certain in the first model and uncertain in the second one.

3.2 Model symbols

Sets
- $C$ : Set of customer center {1...C}.
- $M/R$ : Set of manufacture/remanufacture center {1…R}.
- $R2$ : Set of remanufacture center2 {1…R2}.
- $S$ : Set of storage center {1…S}.
- $T$ : Set of periods {1…T}.

Parameters
- $D$ : Customer demand for masks.
- $CC_{c->r}^M$ : Carrying cost of returned masks M from customer center c to remanufacture center r in period t.
- $CC_{r->s}^M$ : Carrying cost of recycled masks M from remanufacture center r to storage center s in period t.
- $CR_r$ : Remanufacturing cost (sorting, treatment, recycling) in remanufacture center r of 1 kg of masks.
- $CS_s$ : Storage cost in storage center s of 1 kg of recycled masks.
- $PW$ : Price of 1 kg of recycling waste sold to remanufacture center 2.
- $CapR$ : Capacity of remanufacture center.
- $CapS$ : Capacity of storage center.
- $\theta$ : Coefficient of returned quantity of masks.
- $\alpha$ : Coefficient of recycling waste sold to R2.

Decision variables

$Q_{c->r}^M$ : Quantity of returned masks carried from customer center c to remanufacture center r, in period t.
$Q_{r->s}^M$ : Quantity of recycled masks carried from remanufacture center r to storage center s, in period t.
$Q_{r->r2}^W$ : Quantity of recycling waste carried from remanufacture center r to remanufacture center r2, in period t.
$X_{c,r}$ : 1, if remanufacture center r is located at potential site r and set up 0 otherwise.
$Y_{r,s}$ : 1, if storage center s is located at potential site s and set up 0 otherwise.

3.3 Objective function and constraints

Minimizing cost:

$$\text{Min } Z_1 = \sum_t \sum_r C_c^M \times X_{c,r} + \sum_c \sum_s C_{r->s}^M \times Y_{r,s} + Q_{c->r}^M \times CR_r + \sum_s Q_{r->s}^M \times CS_s - \sum_{r2} Q_{r->r2}^W \times PW \times (1)$$

s.t

1. $Q_{c->r}^M = D \times \theta \quad \forall c \in C, \forall r \in R, \forall t \in T (2)$
2. $Q_{r->r2}^W \leq Q_{r->s}^M \times \alpha \quad \forall c \in C, \forall r \in R, \forall t \in T (3)$
3. $Q_{c->r}^M = Q_{c->r2}^W + Q_{r->s}^M \quad \forall r \in R, \forall t \in T (4)$
4. $\sum_c \sum_t Q_{c->r}^M \leq CapR \quad \forall r \in R (5)$
5. $\sum_r \sum_t Q_{r->s}^M \leq CapS \quad \forall s \in S (6)$
6. $\sum_c X_{c,r} = 1 \quad \forall r \in R (7)$
7. $\sum_r X_{c,r} = 1 \quad \forall c \in C (8)$
8. $\sum_s Y_{r,s} = 1 \quad \forall s \in S (9)$
9. $\sum_r Y_{r,s} = 1 \quad \forall r \in R (10)$
10. $Q_{c->r}^M, Q_{r->s}^M, Q_{r->r2}^W \geq 0 (11)$
11. $X_{c,r}, Y_{r,s} \in [0, 1] (12)$
The objective function (1) minimizes the total cost. The first section denotes the transportation cost between the customer center c and the remanufacture center r; the second one denotes the transportation cost between the remanufacture center r and the storage center s; the third section denotes the remanufacturing cost of the returned quantity of masks, in the remanufacture center r; the fourth part denotes the storage cost of recycled masks, in the storage center s, and the fifth section denotes the price of recycling waste sold to the remanufacture center r2. Constraint (2) denotes the quantity of returned masks based on the client demand. Constraint (3) denotes the quantity of recycling waste sold to the remanufacture center r2, based on the returned quantity. Constraint (4) balances the quantity of returned masks. Constraint (5) determines the remanufacturing center capacity. Constraint (6) determines the storage center capacity. Constraint (7) (8) (9) (10) determine the binary algorithm. Constraint (11) represents non-negative decision variables. Constraint (12) determines whether a decision variable is one or zero.

3.4 Cplex model inputs and results

We considered a supply chain which contains 2 customer centers c, 2 manufacture/remanufacture centers r, 2 storage centers s, 2 remanufacture centers r2, during 10 periods. The first model has a deterministic client demand “D”, and the second model follows a stochastic one.

Model 1(certain demand): Deterministic approach
C: customer, M: manufacture, R: remanufacture, S: storage, Q: quantity.

Table 1: Clients demands (kg) in 10 periods.

| Period | C1 demand | C2 demand |
|--------|-----------|-----------|
| 1      | 10        | 30        |
| 2      | 20        | 40        |
| 3      | 15        | 25        |
| 4      | 30        | 40        |
| 5      | 35        | 15        |
| 6      | 25        | 20        |
| 7      | 30        | 30        |
| 8      | 25        | 35        |
| 9      | 35        | 40        |
| 10     | 40        | 40        |

Table 2: Carrying cost (mu) of returned masks from customer center to manufacture/remanufacture center.

| C center | M/R center 1 | M/R center 2 |
|----------|--------------|--------------|
| 1        | 7            | 4            |
| 2        | 5            | 8            |

Table 3: Carrying cost (mu) of recycled masks from manufacture/remanufacture center to storage center.

| M/R center | S center 1 | S center 2 |
|------------|------------|------------|
| 1          | 5          | 7          |
| 2          | 8          | 4          |

Table 4: Remanufacturing cost (mu).

| M/R center | Remanufacturing cost |
|------------|----------------------|
| 1          | 50                   |
| 2          | 40                   |

Table 5: Storing cost (mu).

| S center | Storing cost |
|----------|--------------|
| 1        | 20           |
| 2        | 30           |

Table 6: Waste price (mu).

| R center | Waste price |
|----------|-------------|
| 1        | 20          |
| 2        | 20          |

For the capacity values, we have applied a constraint relaxation, in which we have assumed that the remanufacture and the storage center capacity are unlimited. Given the important amount of data, we preferred to present in this section only quantity values related to one customer center, one manufacture/remanufacture center, one storage center, and one remanufacture center.

Results

Table 7: Quantity of masks (kg) transported to manufacture/remanufacture center, to storage center, and to remanufacture center, in 10 periods.

| Period | Q to M/R center 1 | Q to S center 1 | Q to R center 1 |
|--------|-------------------|----------------|----------------|
| 1      | 7                 | 4.2            | 2.8            |
| 2      | 14                | 8.4            | 5.6            |
| 3      | 10.5              | 6.3            | 4.2            |
| 4      | 21                | 12.6           | 8.4            |
| 5      | 24.5              | 14.7           | 9.8            |
| 6      | 17.5              | 10.5           | 7              |
| 7      | 21                | 12.6           | 8.4            |
| 8      | 17.5              | 10.5           | 7              |
| 9      | 24.5              | 14.7           | 9.8            |
| 10     | 28                | 16.8           | 11.2           |

Table 8/9: Binary variables Xcr/Yrs.
Table 1 represents different clients demand in 10 periods, table 2 represents the different transport costs from 2 customer centers to 2 M/R centers, table 3 represents the different transport costs from 2 M/R centers to 2 storage centers, table 4 represents the remanufacturing costs of the 2 M/R centers, table 5 represents the storing costs of the 2 remanufacturing centers, table 6 indicates the price of kg of waste sold from the remanufacturing center, table 7 represents the different quantities (kg) transported to manufacture /remanufacture center, to storage center, and to remanufacture center, in 10 periods, and table 8/9 indicate the binary variables to choose the appropriate transport cost.

According to these results, we obtain the cost value equal to 24049€. This cost will be used as a standard value noted as “C” , to study the fluctuation impact of client demand for the model 2 below:

**Model 2 (uncertain demand): Stochastic approach**

The demand in this example follows a stochastic distribution given the unclear conditions of a pandemic. Every execution process of the model (results generation) gives us different costs and different quantity results. The 2 tables below with their corresponding graphs show different cost values and cost gaps, the first one when the demand follows random distribution and the second one when it follows inverse normal law distribution with expectation=40 and standard deviation=15 (I chose the inverse Gaussian law because it belongs to exponential family, plus the positive values it generates).

**Table 10: Cost values under random distribution.**

| Generation | Cost  | Cost gaps |
|------------|-------|-----------|
| 1          | 20507 | 3542      |
| 2          | 18580 | 5469      |
| 3          | 22297 | 1752      |
| 4          | 21130 | 2919      |
| 5          | 20066 | 3983      |
| 6          | 24210 | 161       |
| 7          | 20595 | 3454      |
| 8          | 21214 | 2835      |
| 9          | 20920 | 3129      |
| 10         | 20619 | 3430      |
| 11         | 22404 | 1645      |
| 12         | 22255 | 1794      |
| Average    | 21233,08 | 2842.75   |

**Table 11: Cost values under inverse normal law.**

| Generation | Cost  | Cost gaps |
|------------|-------|-----------|
| 1          | 26322 | 2273      |
| 2          | 25639 | 1590      |
| 3          | 24885 | 836       |
| 4          | 23729 | 320       |
| 5          | 25154 | 1105      |
| 6          | 23609 | 440       |
| 7          | 24550 | 501       |
| 8          | 22229 | 1820      |
| 9          | 26302 | 2253      |
| 10         | 22512 | 1537      |
| 11         | 25065 | 1016      |
| 12         | 26502 | 2453      |
| Average    | 24708,16 | 1345.33   |

**Graphs:**

- **graph 1: Cost fluctuation under stochastic approach.**
- **graph 2: Cost fluctuation under inverse normal law distribution.**
3.5 Result analysis

Our main target is to identify which approach gives us the most reliable results, close to the deterministic conditions. When adopting stochastic distribution, value of gaps between the standard value C and costs generated under stochastic approach are more important than ones under inverse normal law distribution.

When comparing the average of costs in the 2 cases, we can conclude that the costs average under inverse normal law distribution is almost equal to the C value.

Thus, we can admit that inverse normal law distribution gives us the most appropriate results.

Given the uncertain situations, costs tend to rise significantly. Therefore, in our case (covid19 pandemic and increase of masks waste), we must test the robustness of the model in order to ensure that all the possible variables are well integrated, we can help achieve this by adding different artificial intelligence extensions.

These procedures will help companies put the right decisions in the right place and time.

4. CONCLUSION

Circularity is our last potential solution to save our environment from resources depletion and pollution, specially in our case of pandemic and the huge increase of medical waste. It is an economic system where we get rid of the take-make-waste cycle and enhance investments to take and make in a closed-loop with zero waste. This goal is achievable only by encouraging circular thinking, which is based on addressing things before they become a problem.

One of the key points mentioned in the United Nations climate change conference in 2021 (COP26), is to encourage the fast transition to renewable energies. According to Ellen MacArthur foundation, considering only energy transition as an only solution to tackle climate change problem is like reading a half book or watching a half film, because the circular economy can address climate change by reducing emissions from industry, land use and agriculture in addition to its ability to built a resilient economy. Therefore, economists, engineers, decision-makers, and entrepreneurs need to change their linear mindsets and mobilize capital towards circular economy solutions as well as, governments need to set enabling policies and put the necessary infrastructure in place.

In this regard, we should increase sustainable development research and encourage designing different green supply chains to pave the fastest and most efficient road to circularity. This paper like all papers, contains limits and could be more extended for example by adding to the chain another form to collect disposable masks like municipalities or contractors, adding the vehicle routing problem, in addition to a real study case to validate the results.

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