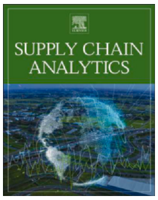
Supply Chain Analytics 3 (2023) 100020

Contents lists available at ScienceDirect

Supply Chain Analytics

journal homepage: www.sciencedirect.com/journal/supply-chain-analytics



A Bi-objective cap-and-trade model for minimising environmental impact in closed-loop supply chains

Massimiliano Caramia[*], Emanuele Pizzari

Dipartimento di Ingegneria dell'Impresa, University of Rome "Tor Vergata", Via del Politecnico, 1-00133 Rome, Italy

A R T I C L E I N F O

Keywords:
Closed-loop supply chain
Multi-objective optimisation
Cap-and-trade policy
Consumer environmental awareness
Government subsidy
Emissions

A B S T R A C T

A Closed-Loop Supply Chain (CLSC) is a complex network with unique environmental features and attributes that requires specific managerial policies and strategies. Quantitative models can provide a solid basis for these policies and strategies. This study expands the work of Shoaeinaeini et al. (2021) on Green Supply Chain Management. We propose a bi-objective facility location, demand allocation, and pricing model for CLSC networks. The proposed model considers two conflicting objective functions: maximising profits and minimising emissions. We show consumer environmental awareness can predict the products' rate of return and determine a more suitable price for new products and the acquisition price for used products. The cap-and-trade policy has been implemented at its fullest potential, allowing the trading of carbon quotas. Therefore, companies may decide to produce less to sell more quotas or vice-versa, effectively picking the most profitable option. The model is solved and tested with the commercial solver BARON. The model effectively shows the trade-off between generating profits and emission reduction. Companies are able to turn a profit while abiding by the government's intention of reducing emissions. The comparison with a single-objective version of the model highlights that the concurrent optimisation of economic and environmental objectives yields better results. The acquisition price of used products is a value worthy of monitoring. The government should focus on policies to assist the reverse flow of used products.

1. Introduction

The concept of Supply Chain is well-known and established. A Supply Chain encompasses all those activities that transform raw material into a finished product, which is then sold to customers [1]. After being used, products are disposed of in specific facilities (Fig. 1). This flow of products goes from suppliers to customers and disposal centres linearly. This concept of 'produce, use, and dispose' has been referred to as Linear Economy [2].

Over the years, due to the rising importance of sustainability, the concept of Supply Chain has expanded to include Green activities, such as Green design and Green transportation. A Supply Chain including Green activities is called Green Supply Chain (GSC) [3]. Moreover, 'produce, use, and dispose' has been surpassed by 'reduce, reuse, and recycle'. The 3Rs are the foundation of the Circular Economy [4]. Products are no longer immediately disposed of after use; instead, they are put back in the supply chain in order to generate additional value. The presence of this reverse flow needs a specific definition of the Supply Chain, the Closed-Loop Supply Chain (CLSC). The reverse flow starts from customer zones and goes back toward the plants. Products are recovered and may be used as raw materials for other products or sold again for a lower price (Fig. 2). Re-manufacturing products can generate conspicuous savings on production costs and energy and reduce pollution [5]. Moreover, companies are still able to turn a profit [6]. Collecting used items and using them for re-manufacturing also decreases the amount of waste that needs to be taken care of.

Nonetheless, rising public environmental awareness has increased the attention of governments and policy-makers. In order to encourage the implementation of re-manufacturing activities, the EU has issued the WEEE Directive [7], although limited to electrical and electronic equipment. Public environmental awareness also positively impacts the number of recoverable products and the price that companies can decide for green products [8]. In fact, consumers with higher awareness are willing to pay higher prices for sustainable products [8]. Moreover, the aforementioned reverse flow is dependent on customers willing to give back the used products instead of disposing of them.

The rising concern for sustainability has also focused on the amount of CO_2 emitted during production and transportation. [9] conducted a

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[*] Corresponding author.
E-mail address: caramia@dii.uniroma2.it (M. Caramia).

https://doi.org/10.1016/j.sca.2023.100020
Received 9 March 2023; Received in revised form 11 May 2023; Accepted 11 June 2023

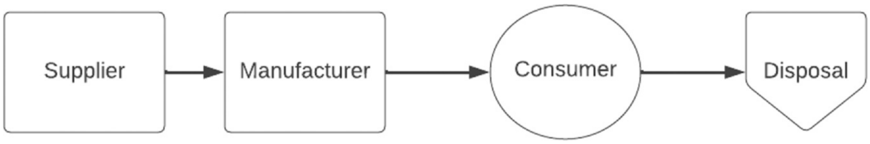

Fig. 1. Forward flow in a Supply Chain.

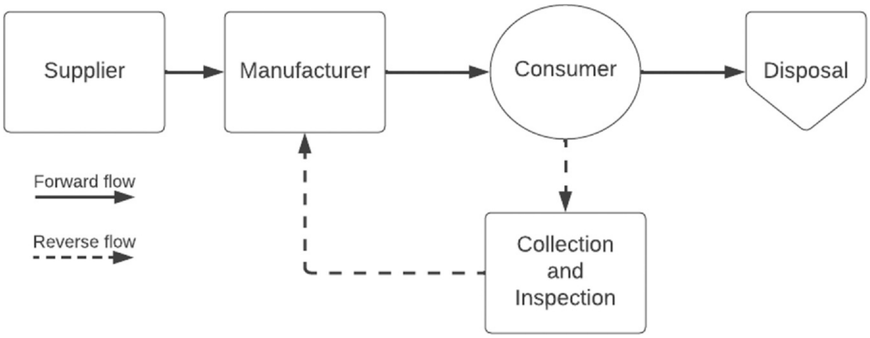

Fig. 2. An example of a Closed Loop Supply Chain.

survey showing the dependency between CO_2 emissions and economic growth. However, in the last few years, due to public attention, policymakers have deployed several policies to reduce carbon emissions. Two central policies are carbon tax and cap-and-trade. [10] compared the two approaches. Carbon tax effectively increases the cost of productive and operational activities by putting a price on carbon emissions. Therefore, the effect of emissions is direct and more visible. Challenges to the design of a proper carbon tax are investigated by [11]. The cap-and-trade policy also puts a limit on the amount of possible emissions. However, companies with emissions lower than the limit are able to sell the remaining quotas. Quotas are then bought by companies that are not able to meet the limit. By buying this permit to emit, they are able to meet their production objective. In the long term, companies are incentivised to reduce the overall emissions they produce in order to be able to sell higher quotas or avoid buying any. The application of the cap-and-trade policy has been investigated in several fields, such as warehouse management [12], and reselling and remanufacturing [13,14]. Recently [15], investigated the effect of blockchain technology on the operations of a supply chain under a cap-and-trade regulation. [16] analyses the advantages and disadvantages of the cap-and-trade policy and how it could be exploited by manufacturers if the policymaker is not careful with the implementation.

Given the multitude of tasks involved and considering the different factors, such as consumer awareness and carbon emissions, managing a CLSC is difficult. Due to the aforementioned management complexity, companies may decide not to transform their business scheme. Therefore, our problem statement is *“it is vital to assist companies by proposing decision models able to capture the nuances of reality and produce feasible solutions. The study of CLSC is also essential for policy-makers, who would be able to infer the necessary policies to support changes toward sustainable production. In these models, the citizens’ behaviour may play a major role in determining the effect of the implemented policies.”* The research question is as follows: *“Is there a way to provide a mathematical model of a CLSC taking into account environmental and economic objectives while considering the effects of customers’ awareness?”*.

1.1. Contribution

The model presented here stems from the one described in [17], where the authors proposed a single-objective model dealing with facility location, demand allocation, and pricing definition. Each production centre can decide to produce between two specific green levels. Used products are then collected, recycled, and sold to secondary markets. Revenues incoming from governmental subsidies for green production are taken into account. Moreover, the model focuses on CO_2 emissions by implementing a cap-and-trade policy. The model puts a cap on the number of possible emissions emitted due to transportation, production, and other operational activities.

We transformed the single-objective model into a bi-objective model, expanding the potentialities of the model. The two objective functions pursue the maximisation of profit and the minimisation of emissions. The price of new and recovered products is no longer associated with each production centre. Instead, a different price is decided for each customer zone and secondary market. Indeed, pricing is dependent not only on production activities but also on the specific zone in which products are sold [18]. The original model included two possible green levels for products. A product with green level 1 would be entirely recyclable, while a product with green level 0 could not be recycled. We expanded this philosophy by increasing the number of intermediate available green levels, meaning that a product could also be partially recycled. Moreover, the cap-and-trade policy is applied to its fullest potential by allowing the trade of carbon quotas, which is not taken into account in [17].

In summary, these are the changes implemented:

- Multiobjective model, separating the environmental and the economic objective.
- Prices of products are associated with the customer zones instead of the production centres.
- Multiple intermediate green levels to increase the versatility of the model.
- The full implementation of the cap-and-trade policy. In their paper, [17] only included the limit on the emissions, ignoring the possibility of selling/buying quotas, which we think is the core of the policy.

2. Literature review

CLSC has garnered much interest from researchers [19–21]. Pricing is a primary focus. [22] consider a three-echelon supply chain with forward and reverse flow. Three objectives are considered: satisfaction of price expectation, the satisfaction of fulfilment rates, and profit. In this model, the price is considered uncertain. [23] and [24] focused on providing models with the definition of optimal acquisition pricing for used products, [25] focused on pricing for new and remanufactured products, while [26] jointly optimised pricing for these three categories. [17] presents a model that links the pricing of a new product to customers’ environmental awareness. [27] proposed a supplier network considering three customers group and their willingness to pay more if products had specific features.

Another focus is on CO_2 emissions and carbon policies. [28] define a multi-product, multi-period CLSC model with a cap-and-trade policy regulating the amount of greenhouse gas emission level. The cap-and-trade policy not only reduces emissions but also generates additional profit. [29] surveyed supply chain networks under carbon emission. [30] apply the cap-and-trade policy to a CLSC, providing a decentralised and a centralised model. [31] investigates retailers' competition and cooperation in a closed-loop green supply chain consisting of one common manufacturer and two competing retailers under governmental intervention and cap-and-trade policy. [32] focuses on CLSCs that consider a carbon tax, carbon cap, and cap-and-trade policy. They deal with demand uncertainty by devising a robust model using a scenario-based Conditional Value-at-Risk. [33] designs a CLSC considering environmental, economic, and social objectives, namely energy consumption, profit, and the number of created job opportunities. They also develop a set of efficient Lagrangian relaxation reformulations and fast heuristics.

CLSC calls for the optimisation of several tasks at once. Therefore, it is natural to assume that there are several objectives, perhaps in conflict with each other. Multi-objective optimisation is preferable when dealing with several objective functions with one decision-maker (or several with the same leverage).

A multi-objective program presents the optimisation of several objective functions at once. The general formulation is the following:

$$\min f_1(x), f_2(x). .f_n(x) \tag{1}$$

$$x \in X \tag{2}$$

for $n \geq 2$. Solving a multi-objective program means finding the trade-off between the objective functions. These trade-off solutions generate the Pareto-optimal front. There are several methods for generating a Pareto-optimal front. The most known classical approaches are weighted-sum and ϵ-constraints [34]. Albeit effective, the weighted-sum approach fails to identify the trade-off solutions lying on non-convex portions of the Pareto-front. Therefore, the ϵ-constraint method is more indicated for problems featuring non-convex objective spaces. This classical method was formulated by [35]. It consists of reformulating $n-1$ objective functions into constraints. Therefore, the multi-objective model becomes a single-objective model. There are several other methods in Literature. For a thorough knowledge of multi-objective optimisation, the reader is referred to [34].

Multi-objective optimisation has been extensively applied to CLSC problems. [36] develop a multi-objective model for inventory and production management in GSC, while [37] focus on the generation of biofuels for forest waste. Other fields of GSC in which multi-objective optimisation has been employed include used car resale [38], dairy industry [39], food supply chain planning problem with returnable transport items [40], and medical device manufacturing [41]. [42] defined a multi-objective model for the design of a sustainable supply chain network. They consider price-sensitive demand and consumer incentives while optimising costs and emissions. [43] develop a two-stage model for a sustainable closed-loop supply chain with pricing and advertising decisions. The cap-and-trade policy has been explored for defining the CLSC of perishable product [44]. [45] define a multi-objective fuzzy robust stochastic model for designing a sustainable-resilient-responsive supply chain network. They consider economic and environmental objectives, social impact, and responsiveness, further applying it to a case study in the water heater industry. [46] consider a closed-loop supply chain with a heterogeneous fleet. They provide several models under a carbon tax or cap-and-trade policy, analysing the respective advantages and disadvantages. [47] applied the cap-and-trade policy to a green supply chain design problem where the government tries to push for an environmental approach. [48] analyses the impact of uncertainty in demand and recovery rate of products on the economic, environmental, and social sustainability aspects in the CLSC.

A multiobjective model featuring customers' classification, pricing, sustainability, and cap-and-trade altogether is missing in the literature. Therefore, the main contribution of this paper is to provide such a model in order to fill the detected literature gap. The remainder of the paper is organised as follows. In Section 3, we describe the problem and its mathematical formulation. In Section 4, we provide experiments; finally, in Section 5, we draw some conclusions.

3. Problem description and mathematical formulation

The underlying functioning and logic of the model are the same as [17]. We will highlight the changes that we made and the reasoning behind them. In this model, a company must locate hybrid manufacturing-remanufacturing centres (HMR), hybrid collection-inspection (HCI) centres, and disposal centres. Each HMR plant produces one product at a specific green level. These products are then sold to customer zones. Producing at one particular green level allows the company to set higher prices for new products and earn revenues from governmental subsidies. After being used, products are repurchased from customers at a specific acquisition price. Products are then inspected in HCI centres and, if deemed feasible for recycling, returned to HMR centres. Recovered products are sold to secondary markets. Products considered infeasible for recycling and products collected from secondary markets are then sent to disposal centres.

Alongside locating facilities, the company needs to set the right acquisition price, dependent on the overall customer environmental awareness and the price of used products. The company also needs to consider the overall emissions due to transportation, production, and other operational activities. Indeed, a cap on carbon emissions is in place. Surpassing this cap results in additional expenses while staying below the limit allows the company to sell remaining quotas to other companies, generating further profit.

The CLSC described is depicted in Fig. 3.

As mentioned before, each HMR centre can decide to produce a new product at a specific green level t. In this model, we assume there are four different green levels instead of the two individuated by [17]:

$$T = \{0, 1, 2, 3\} \tag{3}$$

Level 3 is the highest green level, while level 0 is the lowest. A product with green level 0 is considered non-green and, therefore, non-recyclable. A non-green product does not yield additional profits or additional operational costs. A product with green level 3 is considered fully green (from now on, green) and fully recyclable. Intermediate green levels indicate products that can be partially recycled.

We now provide sets, parameters, and variables used in this model. For ease of presentation, we used the same notation adopted by [17]. Where applicable, we decided to use uppercase letters for sets and lowercase letters for parameters and variables. Any change in notation is indicated in **bold**. Table 1 describes the sets, while Tables 2, 3, 4, 5 and 6 describe the parameters employed in the model. Finally, Tables 7 and 8 describe the binary and continuous variables, respectively.

Cost of production is dependent on the adoption of green activities [17]. It is defined in the following way:

$$cop_{it} = pc_i \cdot bm_i + \beta_i \cdot t^2, \forall\ i \in I, t \in T \tag{4}$$

Green level t affects the unit cost of production in a quadratic way. In fact, a quadratic function is generally used to indicate the cost of eco-friendly improvement since each additional improvement is more complex and more expensive to attain [49].

The price of a new product also depends on the customer's environmental awareness. Given specific fixed customer zones l, with awareness δ_l, the price is defined in the following way:

$$pm_{tl} = Png_l + \delta_l \cdot \alpha_l \cdot t, \forall\ t \in T, l \in L \tag{5}$$

The price of a product is composed of two parts. The first part is the base price of a non-green product (Png_l), while the second is the optional added price of green production activities. The second part

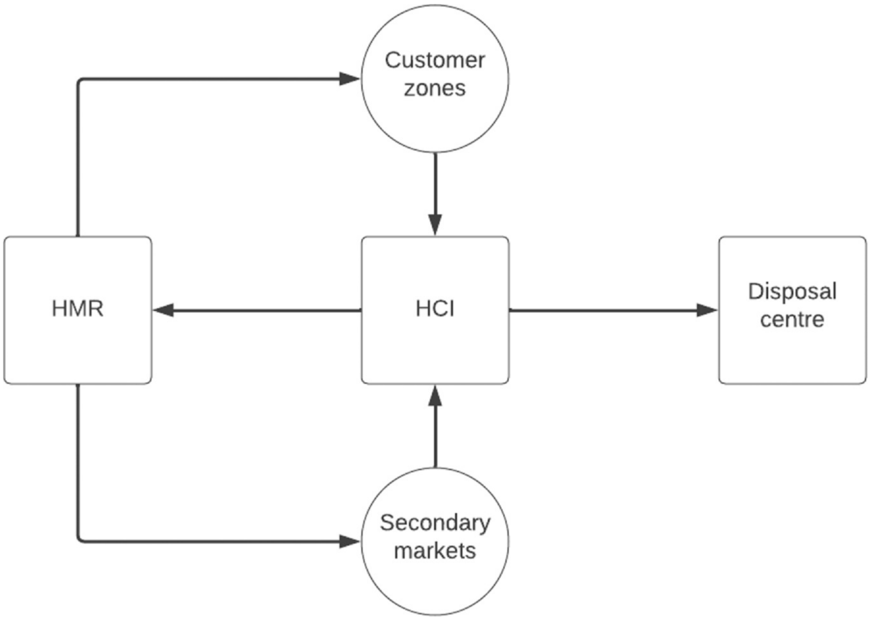

Fig. 3. Closed Loop Supply Chain in this paper.

Table 1
Sets used in the model.

Set	Definition	Index
I	Set of HMR centres	i
J	Set of HCI centres	j
T	Set of green levels	t
K	Set of disposal centres	k
L	Set of customer zones	l
S	Set of secondary markets	s

Table 3
Distance parameters.

Parameter	Definition
t_{il}	Distance between the HMR centre i and customer zone l
t_{lj}	Distance between the customer zone l and HCI centre j
t_{jk}	Distance between the HCI centre j and the disposal centre k
t_{ji}	Distance between the HCI centre j and the HMR centre i
t_{sj}	Distance between the secondary market s and HCI centre j
t_{is}	Distance between HMR centre i and secondary market s

depends on the awareness of the customers' zone. In the case of a non-green product, the price would be the lowest possible (i.e., Png_l).

Fig. 4 is an updated version of Fig. 1; it displays the CLSC with the flow variables described in Table 8. Differently from [17], we decided to split the variables regarding the items produced and the item shipped (and then sold). Indeed, variables x_{it}^1 and represent the number of items manufactured and remanufactured, respectively. On the other hand, variables x_{itl} and m_{is} represent the number of items shipped from a plant to a customer zone. In [17]'s model, any item produced would be sold, even if the quantity produced exceeded the demand. Of course, this would positively affect the final profit, but replicating that logic would be a mistake. Moreover, splitting up the variables between items produced and shipped allows us to more accurately gauge the interest in the green product of each customer zone. We remind the reader that the

Table 2
Cost parameters.

Parameter	Definition
fm_i	Fixed cost of opening HMR centre i
fc_j	Fixed costs of opening HCI centre j
fd_k	Fixed cost of opening disposal centre k
pc_i	Production cost per unit of non-green product at HMR centre i
ic_j	Inspection cost per unit of used product at HCI centre j
rc_j	Recovering cost per unit of recoverable product at HMR centre i
sc_k	Disposing cost per unit of scrap product at disposal centre k
ns_l	Penalty cost per unit of non-satisfied demand of customer zone l
nsr_s	Penalty cost per unit of non-satisfied demand of secondary market s
β_i	The cost factor associated with eco-friendly production at HMR centre i
$\mathbf{cop}_{it}$	Production cost per unit of green product with green level t in factory i
tl_{il}	Transp. cost per unit of product from HMR centre i to customer zone l
tc_{lj}	Transp. cost per unit of returned product from customer zone l to HCI centre j
tr_{ji}	Transp. cost per unit of recoverable product from HCI centre j to HMR centre i
tf_{jk}	Transp. cost per unit of scrap product from HCI centre j to disposal centre k
tm_{is}	Transp. cost per unit of recovered product from HMR centre i to secondary market s
ts_{sj}	Transp. cost per unit of scrap product from secondary market s to HCI centre j

Table 4
Capacity parameters.

Parameter	Definition
cp_i	Maximum capacity of manufacturer i for producing products
cc_j	Maximum capacity of HCI centre j for inspecting products
cs_j	Maximum capacity of HCI centre j for collecting scrap products
cr_i	Maximum capacity of re-manufacturer i for recovering products
cd_k	Maximum capacity of disposal centre k for disposing scrap products
cv	Capacity load of a vehicle

final price is decided according to the quality, the green level of the product, and the zone we are selling to.

As mentioned before, the decision-maker is faced with two different conflicting objective functions. The first objective function aims at maximising the overall profit. it is composed of three different parts. The first part is the following:

$$Z_1 = \sum_{i\in I}\sum_{t\in T}\sum_{l\in L} pm_{tl}\cdot x_{itl} + \sum_{i\in I}\sum_{s\in S} pos_s\cdot m_{is} + \sum_{i\in I}\sum_{t\in T} g_t\cdot x^1_{it}\cdot bp_{it} \tag{6}$$

The first addend computes earnings from selling new products, while the second addend computes earnings from recovered products. We notice that there is a product between two continuous variables, namely pos_s and m_{is}. Therefore, we have a non-convex nonlinear term in this objective function. The third addend computes the governmental subsidies. Once again, there is a non-convex nonlinear term, in this case the product of x^1_{it} and bp_{it}.

The second part of the objective function computes all the expenses. These expenses include the fixed costs of opening centres, variable costs of production and shipping, cost of repurchasing and re-manufacturing, and cost of failed demand satisfaction.

$$\begin{aligned} Z_2 \;=\; & \sum_{i\in I} fm_i\cdot bm_i + \sum_{j\in J} fc_j\cdot bt_j + \sum_{k\in K} fd_k\cdot bu_k + \sum_{i\in I}\sum_{t\in T} cop_{it}\cdot x^1_{it} \\ & + \sum_{i\in I}\sum_{t\in T}\sum_{l\in L} tl_{il}\cdot x_{itl} + \sum_{l\in L}\sum_{j\in J} (ic_j + tc_{lj}) \\ & \cdot q_{lj} + \sum_{j\in J}\sum_{k\in K} (sc_k + tf_{jk})\cdot w_{jk} \\ & + \sum_{j\in J}\sum_{i\in I} tr_{ji}\cdot v_{ji} + \sum_{i\in I} rc_i\cdot m^1_i + \sum_{i\in I}\sum_{s\in S} m_{is}\cdot tm_{is} + \sum_{l\in L} ns_l\cdot r_l \\ & + \sum_{s\in S}\sum_{j\in J} ts_{sj}\cdot ss_{sj} + \sum_{s\in S} nsr_s\cdot rs_s + \sum_{l\in L}\sum_{j\in J} pr\cdot q_{lj} \end{aligned} \tag{7}$$

Finally, the last part implements the cap-and-trade policy. If the company emits emissions lower than the established quota, then these quotas could be sold to turn a profit. On the other hand, if the company fails to meet the quota, it can buy quotas from other companies, resulting in additional expenses. Variables u_i, f_j and e_i are free to assume positive or negative value, depending if we sell/buy carbon quotas, respectively (see Constraints 29–31).

$$Z_3 = \sigma\cdot\left(\sum\nolimits_{i\in I} u_i + \sum\nolimits_{j\in J} f_j + \sum\nolimits_{i\in I} e_i\right) \tag{8}$$

The complete first non-linear objective function is the following:

$$\max Z = Z_1 - Z_2 + Z_3 \tag{9}$$

Table 6
Other parameters used in the model.

Parameter	Definition
d_l	Demand of customer zone l for new products
ds_s	Demand of secondary market s for recycled product
ad	Average disposal fraction
δ_l	The environmental awareness level of customer zone l
Δ	Max amount of δ_l
α_i	The price factor related to eco-friendly production at customer zone l
$\mathbf{pm}_{tl}$	The price of a new product with green level t in customer zone l
Png_l	The price of the non-green product at customer zone l
PNG	Max amount of Png_l
png	Min amount of Png_l
γ_t	Recycling ratio of a product with green level t
g_t	The governmental unit subsidiary of the green product with level t

Table 7
Binary variables used in the model.

Decision variable	Definition
bm_i	1 if HMR centre i is located and set up, 0 otherwise
bt_j	1 if HCI centre j is located and set up, 0 otherwise
bu_k	1 if disposal centre k is located, 0 otherwise
bp_{it}	1 if HMR centre i produces goods with green level t

The second objective function aims at minimising overall environmental emissions.

$$\begin{aligned} \min H \;=\; & ev\cdot\left(\sum_{l\in L}\sum_{i\in I} \frac{t_{il}\cdot x_{itl}}{cv} + \sum_{i\in I}\sum_{s\in S} \frac{t_{is}\cdot m_{is}}{cv}\right) \\ & + ev\cdot\left(\sum_{l\in L}\sum_{j\in J} \frac{t_{lj}\cdot q_{lj}}{cv} + \sum_{j\in J}\sum_{k\in K} \frac{t_{jk}\cdot w_{jk}}{cv} + \sum_{j\in J}\sum_{i\in I} \frac{t_{ji}\cdot v_{ji}}{cv}\right. \\ & \left. + \sum_{s\in S}\sum_{j\in J} \frac{t_{sj}\cdot ss_{sj}}{cv}\right) \\ & + ep\cdot\left(\sum_{i\in I}\sum_{t\in T} x^1_{it} + \sum_{i\in I} m^1_i\right) \end{aligned} \tag{10}$$

The second objective function is composed of three different parts as well. The first part computes the emissions due to the transportation of

Table 5
Emission parameters.

Parameter	Definition
ev	CO_2 emission per distance for shipping products
ep	CO_2 emission for producing and recovering product at an HMR centre
U	Maximum allowable CO_2 emission of transportation for each HMR centre
F	Maximum allowable CO_2 emission of transportation for each HCI centre
E	Maximum allowable CO_2 emission of production for each HMR centre
$\boldsymbol{\sigma}$	Price/cost of a single quota

Table 8
Continuous variables used in the model.

Decision variable	Definition
$\mathbf{x}_{it}^{1}$	Quantity of product with green level *t* produced at HMR centre *i*
$\mathbf{x}_{itl}$	Quantity of new product with green level *t* shipped from HMR *i* centre to customer zone *l*
$\mathbf{m}_{i}^{1}$	Quantity of recovered product produced at HMR centre *i*
$\mathbf{m}_{is}$	Quantity of the recovered product that is shipped from HMR centre *i* to secondary market *s*
q_{lj}	Quantity of the returned product that is shipped from customer zone *l* to HCI centre *j*
v_{ji}	Quantity of the recoverable product that is shipped from HCI centre *j* to HMR centre *i*
w_{jk}	Quantity of the scrap product that is shipped from HCI centre *j* to disposal centre *k*
ss_{sj}	Quantity of the scrap product that is shipped from secondary market *s* to HCI centre *j*
r_l	Quantity of shortage for customer zone *l*
rs_s	Quantity of shortage for secondary market *s*
pr	Purchasing price per unit of a used product of customer
pos_s	The price of a recovered product in secondary market *s*
θ_l	Returning ratio of used products of customer zone *l*
$\mathbf{u}_i$	Available/needed carbon quotas due to transp from HMR centres *i*
$\mathbf{f}_j$	Available/needed carbon quotas due to transp in HCI centres *j*
$\mathbf{e}_i$	Available/needed carbon quotas due to prod from HMR centres *i*

new and recovered products from HMR centres to customer zones and secondary markets, respectively. The second part computes the emissions due to transportation between customer zones and HCI centres, transportation between HCI centres and HMR centres, transportation between secondary markets and HCI centres, and transportation between HCI centres and disposal centres. The last part computes the emissions due to the production of new and recovered products.

We now present the overall formulation.

$$\max Z$$

$$\min H$$

$$x_{it}^{1} \le cp_i \cdot bp_{it} \ \ \forall\, i \in I,\, t \in T \tag{11}$$

$$m_i^1 \le cr_i \cdot bm_i \ \forall\, i \in I \tag{12}$$

$$x_{it}^{1} = \sum\nolimits_{l\in L} x_{itl} \ \forall\, i \in I,\, t \in T \tag{13}$$

$$m_i^1 = \sum\nolimits_{s\in S} m_{is} \ \forall\, i \in I \tag{14}$$

$$\sum\nolimits_{i\in I} \sum\nolimits_{t\in T} x_{itl} = d_l - r_l \ \forall\, l \in L \tag{15}$$

$$\sum\nolimits_{i\in I} m_{is} = d_s - rs_s \ \forall\, s \in S \tag{16}$$

$$\sum\nolimits_{j\in J} q_{lj} \le \theta_l \cdot \sum\nolimits_{i\in I} \sum\nolimits_{t\in T} x_{itl} \cdot \gamma_t \cdot bp_{it} \ \forall\, l \in L \tag{17}$$

$$\sum\nolimits_{i\in I} v_{ji} = (1 - Ad) \cdot \sum\nolimits_{l\in L} q_{lj} \ \forall\, j \in J \tag{18}$$

$$\sum\nolimits_{s\in S} m_{is} \le \sum\nolimits_{j\in J} v_{ji} \cdot bm_i \ \forall\, i \in I \tag{19}$$

$$\sum\nolimits_{j\in J} ss_{sj} \le \sum\nolimits_{i\in I} m_{is} \ \forall\, s \in S \tag{20}$$

$$\sum\nolimits_{k\in K} w_{jk} = Ad \cdot \sum\nolimits_{l\in L} q_{lj} + \sum\nolimits_{s\in S} ss_{sj} \ \forall\, j \in J \tag{21}$$

$$\sum\nolimits_{l\in L} q_{lj} \le bt_j \cdot cc_j \ \forall\, j \in J \tag{22}$$

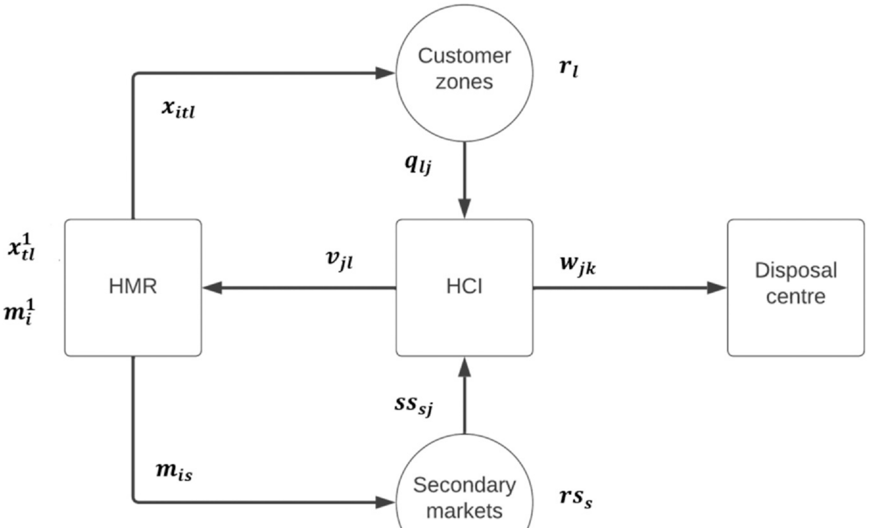

Fig. 4. CLSC with the continuous flow variables.

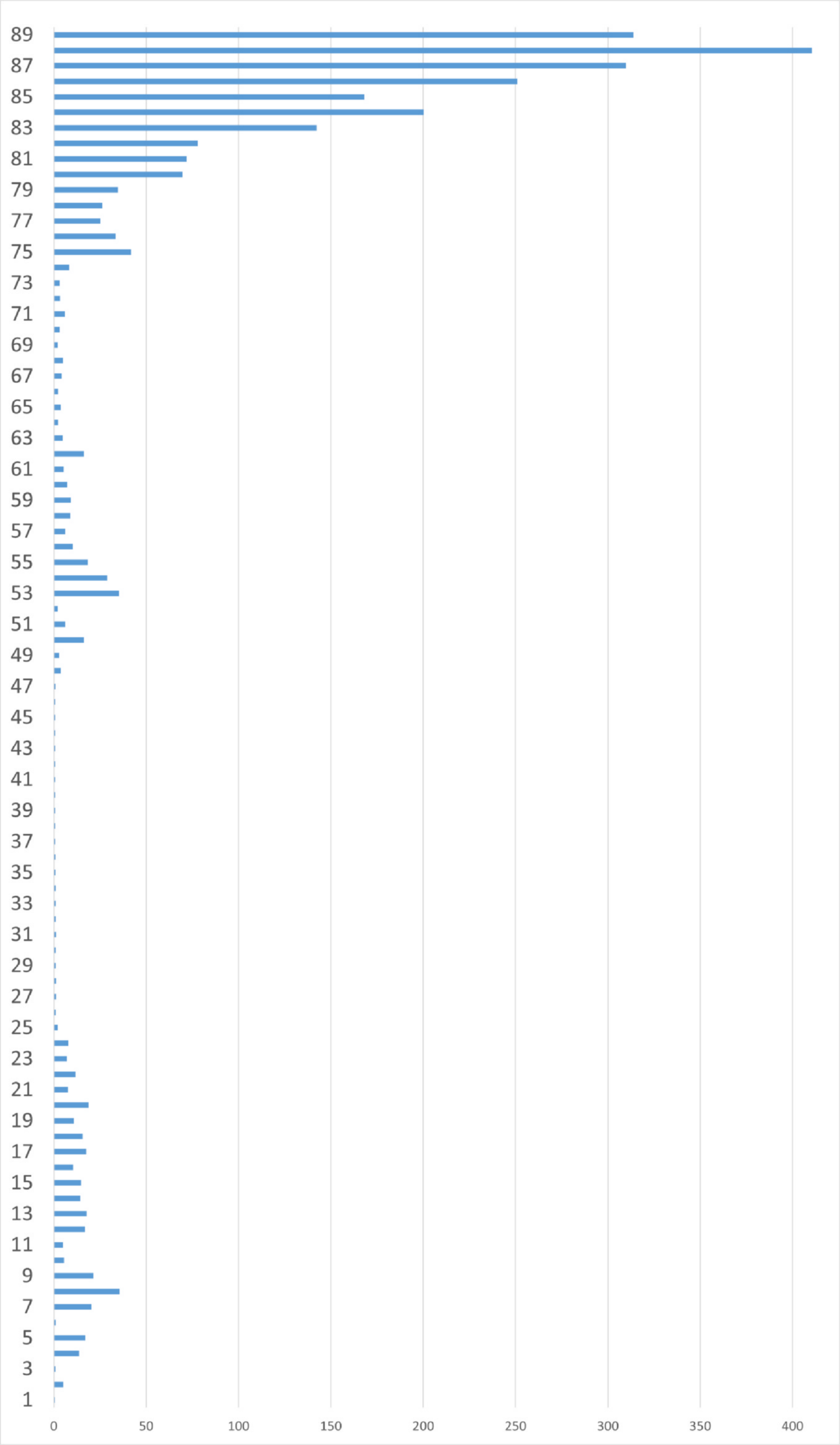

Fig. 5. Computation time needed for each iteration.

$$\sum\nolimits_{s\in S} ss_{sj} \le bt_j \cdot cs_j \ \forall \ j \in J \tag{23}$$

$$\sum\nolimits_{j\in J} w_{jk} \le bu_k \cdot cd_k \ \forall \ k \in K \tag{24}$$

$$\theta_l = \frac{pr \cdot \delta_l}{PNG \cdot \Delta} \ \forall \ l \in L \tag{25}$$

$$\sum\nolimits_{t\in T} bp_{it} = bm_i \ \forall \ i \in I \tag{26}$$

$$pr \le pos_s \ \forall \ s \in S \tag{27}$$

$$pos_s \le Png \ \forall \ s \in S \tag{28}$$

$$U - ev \cdot \left(\sum_{l\in L} \frac{t_{il} \cdot x_{itl}}{cv} + \sum_{s\in S} \frac{t_{is} \cdot m_{is}}{cv} \right) = u_i \ \forall \ i \in I \tag{29}$$

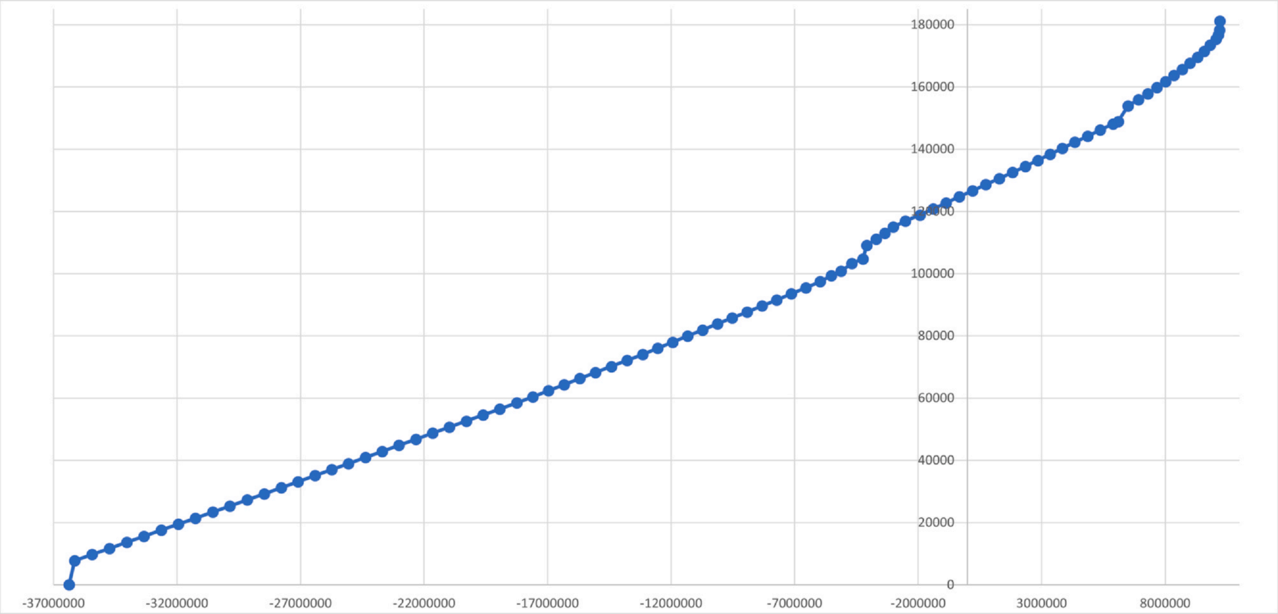

Fig. 6. The Pareto Front.

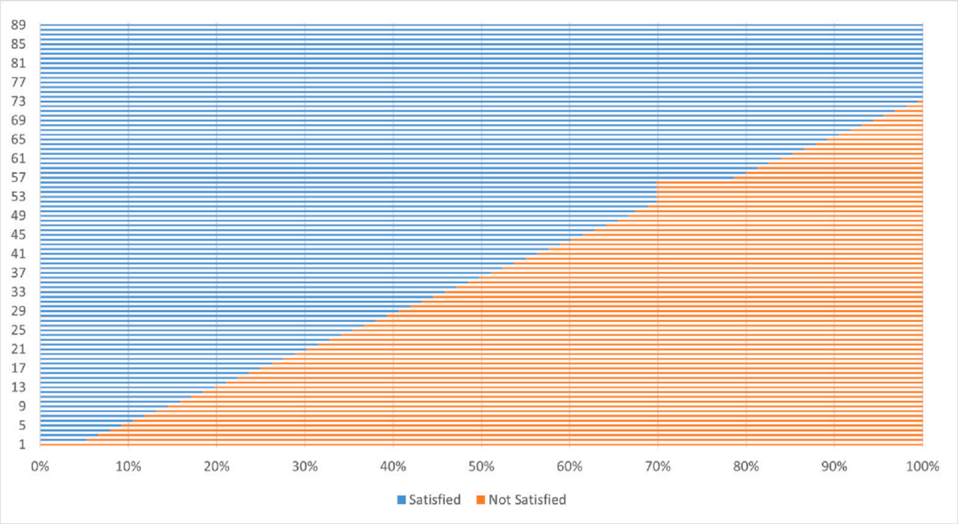

Fig. 7. Percentage of satisfied demand for new products.

$$F - ev \cdot \left(\sum_{l \in L} \frac{t_{lj} \cdot q_{lj}}{cv} + \sum_{k \in K} \frac{t_{jk} \cdot w_{jk}}{cv} + \sum_{i \in I} \frac{t_{ji} \cdot v_{ji}}{cv} + \sum_{s \in S} \frac{t_{sj} \cdot ss_{sj}}{cv} \right) = f_j \;\; \forall\, j \in J \tag{30}$$

$$E - ep \cdot \left(\sum\nolimits_{t \in T} x^1_{it} + m^1_i \right) = e_i \;\; \forall\, i \in I \tag{31}$$

$$x^1_{tl},\, x_{itl},\, m^1_i,\, m_{is},\, q_{lj},\, v_{ji},\, ss_{sj} \geq 0 \;\; \forall\, i, t, l, s, j \tag{32}$$

$$r_l,\, rs_s,\, pr,\, pos_s,\, \theta_l \geq 0 \;\; \forall\, l, s \tag{33}$$

$$bm_i,\, bt_j,\, bu_k,\, bp_{it} \in \{0, 1\} \;\; \forall\, i, j, k, t \tag{34}$$

$$u_i,\, f_j,\, e_i \in \mathbb{R} \;\; \forall\, i, j \tag{35}$$

The aforementioned changes in notation and computation of specific parameters, as well as the introduction of new variables, are obviously reflected in the constraints described here. Constraints (11) and (12) determine the maximum amount of new and recovered products that can be produced in each HMR centre *i*, respectively. Constraints (13) and (14) state that every new and recovered product produced must be sent to customer zones *l* or secondary markets *s*, respectively. Constraints (15) and (16) determine the overall satisfied demand in each customer zone *l* and secondary market *s*, respectively. Constraints (17) define the number of products that customer zones return to HCI centres, according to their return rate θ_l. Constraints (18) define the number of products that HCI centres send to HMR centres for recovery. Constraints (19) state that recovered products for each HMR centre cannot be more than the number of products sent from HCI centres. Constraints (20) define the amount of used recovered products outflowing from secondary markets to HCI centres, while Constraints (21) define the overall amount of disposable products. Constraints (22) and (23) define the maximum available capacity for inspecting used products and collecting used recovered products for each HCI centre, while Constraints (24) define the maximum capacity for disposing of products. Constraints (25) define the return rate for each customer zone. Constraint (26) state that each HMR centre produces product at

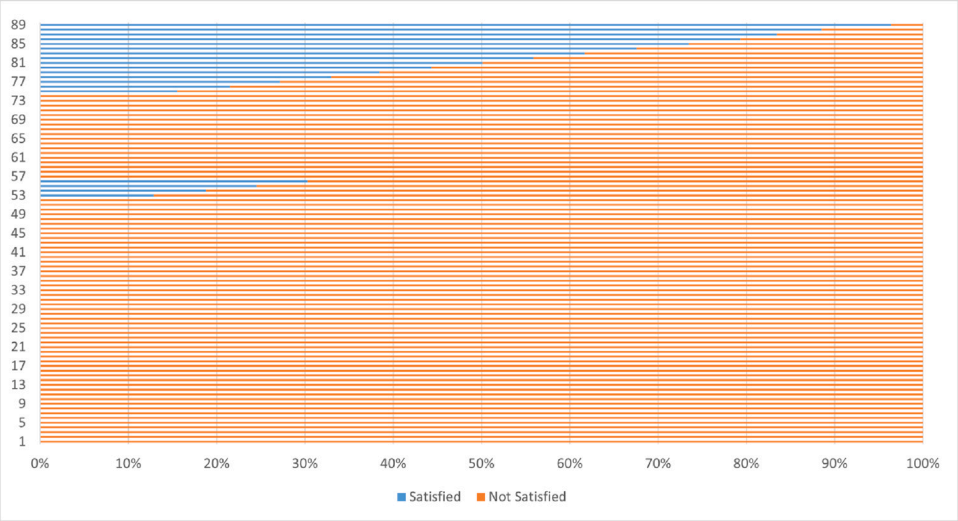

Fig. 8. Percentage of satisfied demand for recovered products.

only one specific green level. Constraints (27) and (28) define the acquisition price and the price of recovered products, respectively. Constraints (29)-(31) define the overall available emissions and, therefore if it is needed to buy more quotas or if it is possible to sell them to turn a profit. Constraints (32)-(35) state the sign of the variables. We notice that constraints (17) and (19) are non-linear.

4. Experimental results and managerial implications

The model has been implemented in the AMPL language on a Windows 11 machine using an AMD Ryzen 7 4800 H processor with 16 GB of RAM. Experiments have been carried out by using the commercial solver BARON.

We tested the model on an illustrative example of an Iranian straw manufacturer. Data is available in [17]. The σ parameter we introduced is assumed equal to 0.1. The bi-objective nature of the model has been dealt with using the well-known ϵ-constraints approach, introduced by [35]. The ϵ-constraints approach solves one of the objective functions while putting the other as a constraint, bounded with the so-called parameter ϵ. In this case, we computed the lower and upper bounds for the second objective function, the environmental objective. We instead focus on optimising the first objective function, the economic objective.

Each iteration has been solved at the optimum. Although, different computational time was needed. Fig. 5 showcases the computation time for solving each iteration. We notice a sharp increase for later iterations. Indeed, given that the constraint on the second objective function is less strict, the complexity is higher. The highest time was needed for the last valid iteration.

The Pareto front of the non-dominated solutions is presented in Fig. 6.

Several iterations fail to make a profit for the companies. Coincidentally, in these iterations, the model attains the lowest amount of emissions. We remind the reader that the company is allowed not to satisfy the entire demand. The not satisfied demand for new and recovered products results in expenses for the company. Fig. 7 depicts the satisfied demand for new products for each iteration. Similarly, Fig. 8 depicts the satisfied demand for re-manufactured products for each iteration.

It is evident that the company fails to satisfy the demand for a lower amount of allowable emissions. Moreover, for these instances, the company decides not to recover products for re-manufacturing. Therefore, pursuing a policy of minimisation of emissions without considering the possible revenues from re-manufacturing damages the closed-loop approach. The not recovered items will be disposed of, further increasing the burden on the waste management supply chain. For each iteration, the company settles for the product with the highest green level, thanks to the additional profit and to the government subsidies that allow reducing the burden of production costs.

The acquisition price of used products changes for each iteration. Fig. 9 depicts the behaviour of the price for iterations yielding losses for the company. Fig. 10 depicts the behaviour of the price for iterations yielding profits for the company. We notice that the acquisition price is zero for some iterations, meaning that the company generates more profits without taking into account the reverse flow. We believe this conclusion to be quite dangerous. From a policy-maker point of view, the priority is environmental sustainability. Perhaps, incentives are enough to push the company to produce green products, but they may be insufficient to guarantee the re-manufacturing of items. Indeed, an exceptionally high level of awareness leads to a high acquisition price, which may cancel any possible profit. Nevertheless, iterations with the highest profit increase employ the re-manufacturing of items, further proving that recycling is a vastly profitable activity. A higher level of emissions counterbalances this.

We also solved the single-objective version of the model, aiming to maximise profit without considering the level of emissions. For ease of presentation, the single-objective model solution is represented in Fig. 11, which encompasses only the Pareto front solutions with positive profit. The optimal single-objective model solution appears to belong to the Pareto front; nonetheless, it is the solution with the highest environmental impact. Studying the model without the second objective function would generate the most damage to the environment. On the other hand, studying the model without the first objective function would provide a trivial solution with huge losses for the company. In fact, the best solution produces zero emissions, which can be achieved only by not producing anything at all. Of course, this solution is quite far from reality. The model would need additional constraints that force the profit to be at least zero, but then it would provide a trivial solution (e.g. the minimum amount of production) again. Therefore, it is advised to pursue studying a multi-objective version in order to properly gather information on optimal green production (companies) and on necessary policies to support sustainability (policy-makers).

We also tested the bi-objective model on the case in which the cap-and-trade policy is only applied by putting an upper bound on possible emissions, effectively removing the possibility of generating additional profits. The Pareto front obtained for this case is similar to the one attained with the cap-and-trade policy in play. As expected, implementing the cap-and-trade allows the generation of higher profits. We do not observe a positive impact on carbon emissions and note that

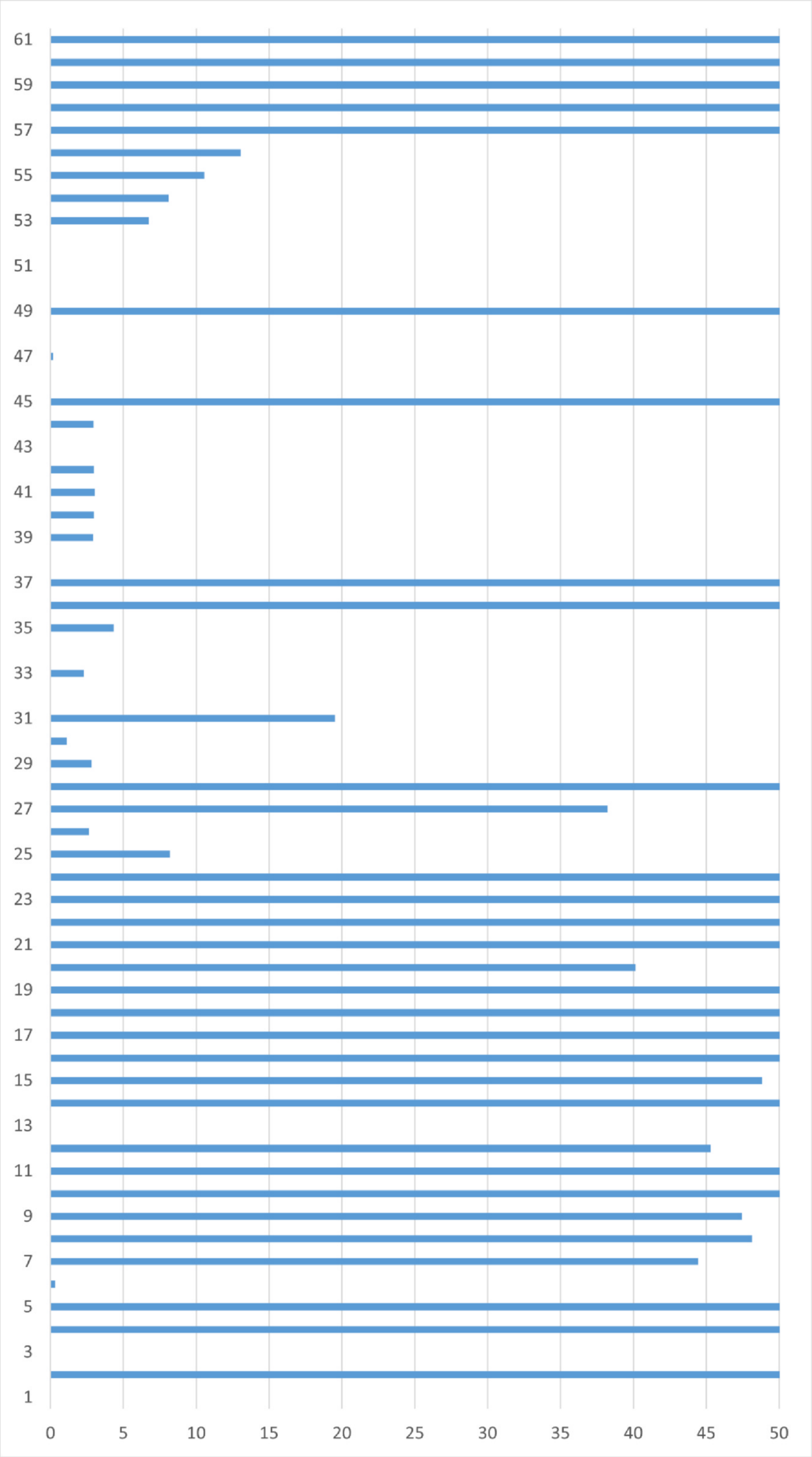

Fig. 9. Acquisition price for losses iterations.

the cap-and-trade policy does not affect the production of new and recovered products for this instance. Indeed, production is mainly affected by the concurrent optimisation of the two objective functions.

We also conducted a sensitivity analysis on several parameters, such as the carbon quota, the price of carbon emissions, and the distance between facilities and customer zones. The results were in line with expectations. The carbon quota severely affects the company's profit: with lower possible emissions, the company still finds satisfying demand to be more profitable, therefore choosing to buy additional quotas from other companies. Although, a sharp decrease in allowable

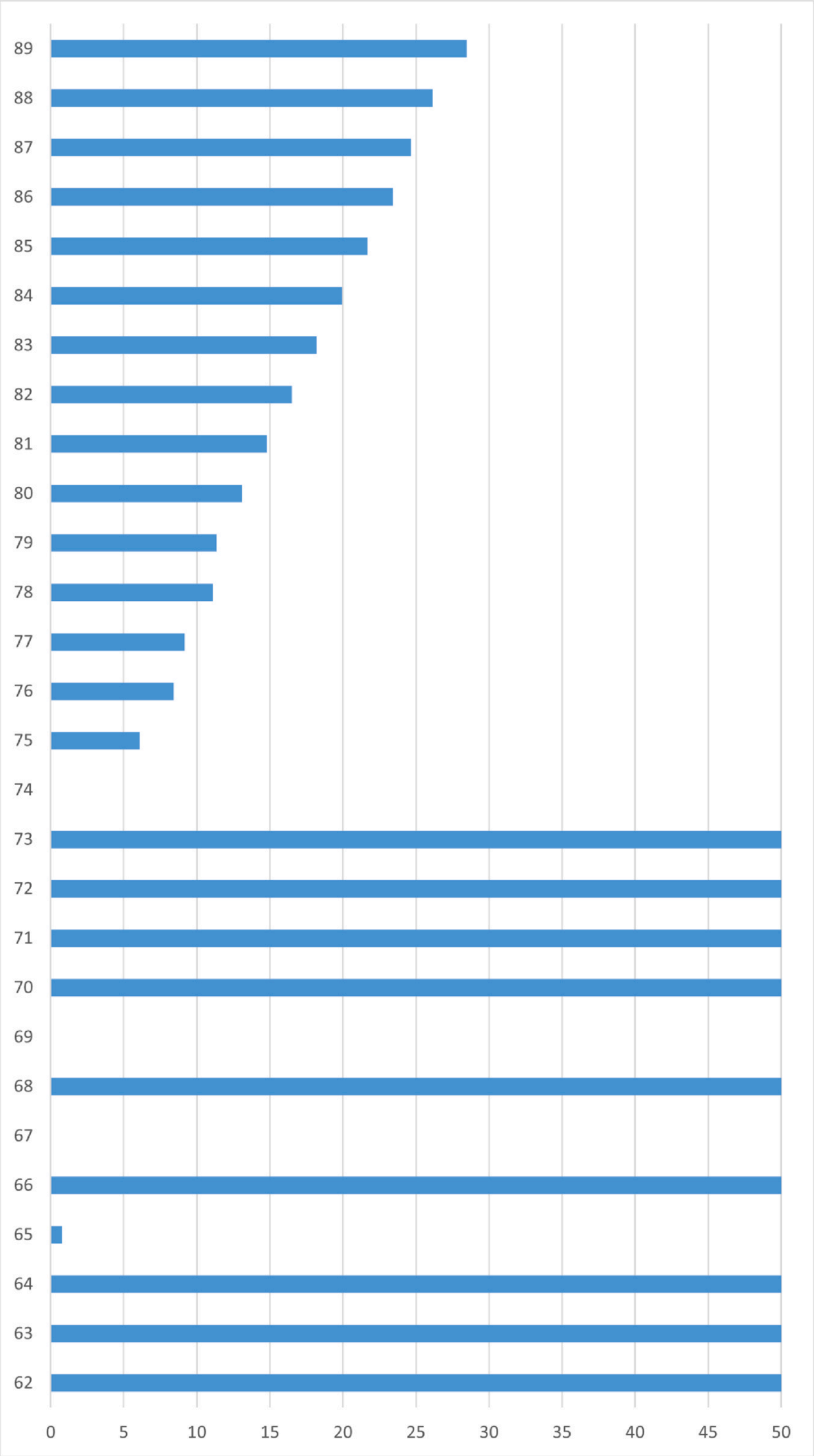

Fig. 10. Acquisition price for profits iterations.

emissions severely hurts profit, as shown in Fig. 12; the amount of allowable emissions is cut by 10 %, causing a massive hit on the company's profitability.

Increasing carbon price makes not satisfying demand more palatable. The company will therefore reduce the number of objects produced in order to keep the expenses at a minimum. However, the reverse flow is the main flow affected, meaning that the company decide not to reclaim the used products. The demand for used products is the most affected in this case. In the long-term, this will perhaps cause several unhappy customers to seek first-hand items, defying the initial will of sustainable CLSC.

We believe the results herein discussed give valuable insight to policy-makers, who may decide to act by reducing the allowable emissions if they believe that companies are still profitable and economically sustainable at a specific quota. On the other hand, they could increase the price of carbon quotas, making the sale more profitable for

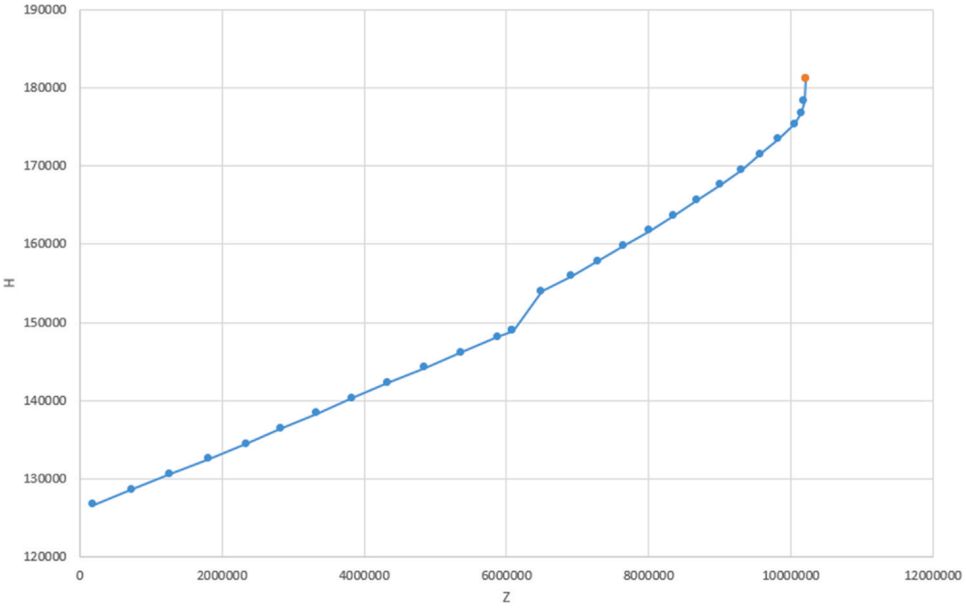

Fig. 11. Single-objective solution compared to the Pareto solutions.

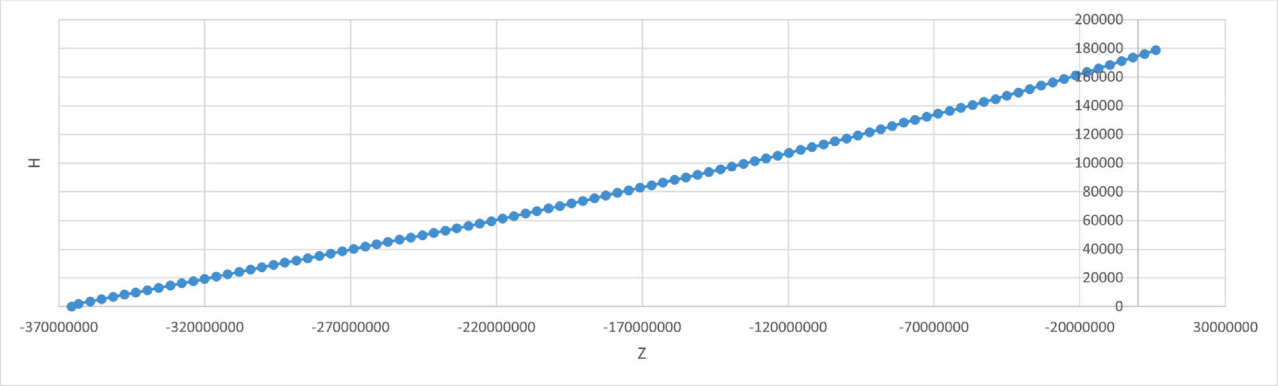

Fig. 12. The new Pareto front with reduced allowable emissions.

companies. Of course, the number of recovered products has to be monitored; the reverse flow should remain economically attractive for companies.

5. Conclusions

In this paper, we expanded the work of [17]. Inspired by their model, we defined a bi-objective facility location, demand allocation, and pricing model. The two objective functions aim at maximising profits and minimising emissions, respectively. Consumer environmental awareness level is taken into account to predict the return rate of products correctly and define the more suitable price of new products and the acquisition price for used products. The cap-and-trade policy has been implemented at its fullest potential, allowing the trading of carbon quotas and possibly pursuing additional profit. The model has been tested on an illustrative example based on an Iranian straw production line.

The bi-objective model has been successfully solved with the ϵ-constraints method, showing the trade-off between generating profits and emission reduction. Because of government incentives and great customer awareness, the corporation always settles for the highest green-level product. Customer zones with little awareness receive items with the greatest green level but do not generate more profit. The price for these zones must be reduced, perhaps jeopardising profitability. Indeed, businesses may choose less expensive non-green alternatives. Governments must create ad hoc policies to raise environmental awareness among customers and make them more appealing. Otherwise, enterprises that are not engaged in green operations would continue to make unrecoverable polluting goods and sell them at a low price, thereby defeating the purpose of a CLSC. Governments also need to implement other policies to assist the reverse flow of products from customers to re-manufacturers. Simply assisting in the production of recoverable products does not guarantee that recovery happens.

A limitation of this model is the deterministic nature of data. Indeed, uncertainty plays a vital role when determining production and, most importantly, recovery. Green levels and customer awareness may be used to infer the probability of collecting products suitable for recycling and deciding the optimal production quantity. We also point out that we decided to use a commercial solver because we focus on the model itself and the managerial implications. Nonetheless, more sophisticated mathematical approaches do exist, and they may be able to provide solutions faster. Moreover, we suggest exploring the potentialities of this model in a multi-period setting. With extensive enough periods, it may be used to test the effect of policies on increasing environmental awareness and, in turn, the profitability of the customer zones.

Data Availability

Data is available in [17].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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