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# A novel multi-objective model for green forward and reverse logistics network design

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ABSTRACT

With a greater awareness of responsibility for the environment and the need to sustain profitability in a competitive market, reverse logistics has become a key part of supply chain management. This paper therefore seeks to consider the designing and planning of a green forward and reverse logistics network, through a mixed integer linear programming model. The model is applied to a multi-stage, multi-product, and multi-objective problem whereby the first objective is to minimize the cost of operations, processes, transportation, and fixed costs of the establishment. The second objective is to minimize the amount of $CO_2$ emissions based on the gram unit, while the third is to optimize the number of machines in the production line. For validation, the model is applied to the home appliance industry through several test problems. In terms of the solution methodology, an epsilon-constraint method is developed as the area of optimization in order to obtain a set of Pareto solutions. Finally, sensitivity analysis is conducted to understand the effects of changes in the demand, cost, and rate of return of the used product, on the objective function values.



## 1. Introduction

Firms face increasing pressure to conform to the environmental, societal, political, and economic demands from a variety of stakeholders such as the community and media (Fleischmann et al., 1997). For many firms, the end of life product recovery is a major issue in product management (Fleischmann et al., 2000), and reverse logistics is a significant part of that (Ayvaz et al., 2015; Hsu et al., 2016). Recently, reverse logistics has attracted the attention of many manufacturers (Govindan et al., 2015) as the reverse logistics activities are related to the recovery process of the end of life products (Govindan and Soleimani, 2017) which are collected from the customers through the collection centers and are assigned either for remanufacturing, recycling, or green disposal (Zarbakhshnia et al., 2018). Many firms have started to apply integrated environmental strategies to improve their business models and competitive advantage through the reuse and recovery process for end-of-life products (Giri et al., 2017). Likewise, governments have introduced legislations to counter the problem of pollution and this affects how firms handle their end-of-life products (Aitken and Harrison, 2013). The notion of reverse logistics applies to the entire lifecycle of a product, from design to consumption, and its subsequent return to the plant (Guarnieri et al., 2016). Rogers and Tibben-Lembke (1999) define reverse logistics as designing, scheduling, and controlling the productive and beneficial flow of products that are at the end of life, inventory and information of the used products from consumer to producer so as to recover, recycle or dispose of the used products. Fig. 1 shows the process of a typical forward and reverse logistics network.

Green logistics is a form of logistics that includes environmental protection and sometimes social issues including the socio-economic criteria (Soleimani et al., 2018). From this perspective, reverse logistics is germane to the green logistics literature as a tool for developing the level of recovery and return of the used products (Shi et al., 2015), serving to reduce pollution and product waste through activities like refurbishing, repairing, remanufacturing,

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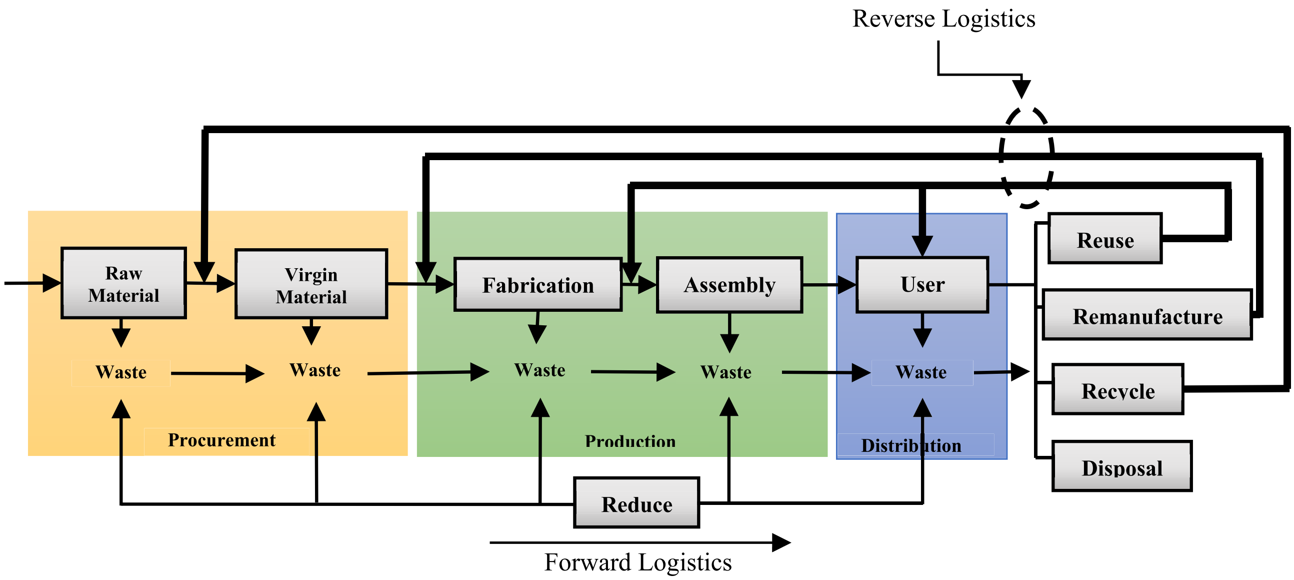


**Fig. 1.** Process of forward and reverse logistics location (Meade and Sarkis, 2002).

recycling, disposal, and parts recovery (Chileshe et al., 2016). Thus, it is imperative to find a way through reverse logistics to increase the proportion of used product returns to the plant so as to protect the environment (Soleimani et al., 2014).

Our research focuses on a multi-stage, multi-objective, and multi-product model for a green forward and reverse logistics network. To illustrate the economic and environmental dimensions, our model seeks to optimize the cost of operations, processes, transportation, and the fixed costs of the establishment, while minimizing the amount of $CO_2$ emitted in the green reverse logistics network and optimizing the number of machines in the production line. The proposed model is applied to the home appliance industry. The epsilon-constraint method is used to solve the mathematical model. To validate the solution procedure, we generate several small-, medium- and large-sized test problems. In summary, the contributions of this paper are as follows:

- We optimize the amount of $CO_2$ in both the forward and reverse flows.
- We minimize the number of machines in the production line with both forward and reverse flows in the green logistics model.
- We apply the epsilon-constraint method to solve green forward and reverse logistics model.
- We apply realistic constraints on the warehousing and customer demand.

The rest of the paper is provided as follows. In Section 2, a literature review is presented. Section 3 discusses the green forward and reverse logistics, multi-objective programming, and the model parameters and variables. The solving methodology is presented in Section 4. The numerical experimentation of the case study are found in Section 5. Section 6 contains the sensitivity analysis and some managerial implications. Section 7 concludes with some research directions.

## 2. Literature review

This paper considers the issue of mathematical modelling of green logistics for the design and planning of a green forward and reverse logistics network. For this purpose, the review of the literature seeks to identify the gaps in designing and planning a green forward and reverse logistics network under mathematical modelling.

The literature reports that green supply chain management can improve the effectiveness of enterprises (Zhu and Sarkis, 2004). The increasing effectiveness of firms through environmental activities is usually related to the integration strategies and economic performance that can improve manufacturing and production sustainability (Zarbakhshnia and Jaghdani, 2018). Indeed, these are the criteria that can lead to sustainable, competitive advantages for firms, differentiating them from the others as ‘green’ enterprises (Rao and Holt, 2005).

The structure of green production comes from the integration of economic and environmental issues (see Fig. 2). It includes eco-friendly design, green packaging, green design (eco-design), and sustainable products (Khor and Udin, 2013). For competitive advantage in green production, organizations should carry out scientific research and development, be more creative, identify the demands of the market, recruit talent, and expand their knowledge. Thus, green production is a scientific process (Mills et al., 2003). The objectives of green production are to design products with the least use of environmental resources and to decrease the emission of greenhouse gases (Kuo et al., 2001).

Reverse logistics is key to green supply chain management. It helps achieve better performance and can be an opportunity for firms to see an increased rate of return of the end-of-life products (Guo et al., 2017a, b). These end-of-life products are

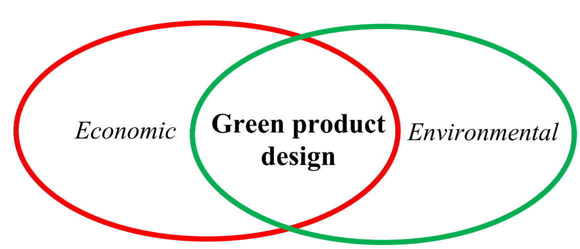


**Fig. 2.** Dimensions of green product design. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

remanufactured and recycled, or disposed, to become raw materials or revived products, which ultimately lead to gains for customers (Mavi et al., 2017).

Fleischmann et al. (2000) modelled green reverse logistics for the first time with some environmental factors, and then applied them to the reverse supply chain for the purpose of designing and planning. Several recent studies have also focused on reverse logistics. Hu et al. (2002) proposed a discrete-time, linear analytical and multi-product (hazardous-waste) and multi-period model to minimize the operation cost. They provided some constraints to consider business strategies and governmental issues with internal and external metrics. Quariguasi Frota Neto et al. (2010) designed a closed-loop supply chain for a recycling system. They explored some environmental strategies with many economic and environmental criteria, and used a software called ADBASE to solve the model. Cardoso et al. (2013) designed and planned a supply chain network with reverse flows and established production, distribution, and reverse logistics centers. They considered the demand uncertainty and the objective function for the maximization of the net present value, in order to identify the size and location of the centers, warehouses, and retailers. Ramezani et al. (2013) suggested a stochastic multi-objective model for both forward and reverse logistic network designs in a way that two stages and three stages were considered for reverse and forward logistics, respectively. Their objectives were to maximize the benefits and optimize customer responsiveness and quality under an uncertain environment. Zohal and Soleimani (2016) provided a multi-objective model that considered a closed-loop supply chain involving four stages of forward flow and three stages of reverse flow. They considered an actual case study in the gold industry where $CO_2$ emission was a significant consideration. Table 1 illustrates the reviewed literature on green reverse logistics, in various aspects of research such as the number of products and objectives, the solution method, and the decision level. Through Table 1, the gaps in the existing body of research on green reverse logistics are identified.

The present research is a multi-stage, multi-objective, and multi-product model for a green forward and reverse logistics network. To illustrate the economic and environmental dimensions, the provided model optimizes the value of the cost of operations, processes, transportation, and the fixed costs of the establishment. Further, the objective functions of the model are to optimize the amount of $CO_2$ in the green reverse logistics networks and to minimize the number of machines in the production line. To solve the model, an epsilon-constraint method is applied. The proposed model is applied to the home appliance industry. In addition, the model and solution method are validated through several small, medium, and large-sized test problems.

## 3. Multi-objective green logistics model

We now begin to model the problem. First, the problem is presented. Then, the model assumptions, indices, parameters, and decision variables of the mathematical model are specified. Thereafter, the formulation of the model is presented. Finally, the equations and constraints of the model are presented.

### 3.1. Problem definition

In this research a multi-objective optimization model is formulated to minimize the respective costs, $CO_2$, and number of machines. The main problem in the study is reducing the costs which is the most significant issue for each firm to achieve more profit, for this matter the first objective function (minimization of cost) and the third one (minimization of number of machines) are determined. Additionally, the nature and content of a reverse logistics strategy is frugality in using raw material and recovering end of life products which directly help to decrease the costs as well as protect the environment as the second objective of this problem. Hence, this model is proposed for firms which have forward logistics (supplier, manufacturer, and distributor center, and warehouse) and they are trying to operate reverse logistics. Also, regardless of the recycling and disposal centers as main nodes in reverse logistics, the remanufacturing and revival centers of the provided model can also apply to the manufacturing companies.

The schematic of the forward and reverse logistics network is presented in Fig. 3, which identifies two flows in the network. The first is a forward flow which starts from the supplier centers in which raw materials are transported to the manufacturing centers where the goods are produced. Some of these products are delivered to the distribution and collection centers, and the rest are stocked in the warehouses. Finally, the products are distributed to the customers. The second flow starts from the customer areas (end point of the forward flow), whereby the returned products are sent to the distribution and collection centers, and the products are handed over for remanufacturing, recycling, and disposal. In the remanufacturing centers, the products are repaired and re-sent to the manufacturing centers to complete the production process or are disassembled into components for delivering to the suppliers. Also, in the recycling centers, the products are turned to raw material and parts; the parts are then sent to the manufacturing centers, and the raw materials are sent to the supplier centers.

### 3.2. Model assumptions

The assumptions of the proposed model are as follows:

- The model is single-period but multi-product.
- The demands of the customers and the amount of returned products are known and certain.
- All the returned products are collected and all the demands must be met.

**Table 1**
Summary of green reverse logistics literature review design and planning.

| No. | Source | Year | Product | Objective | Solution method | Approach | Decision level |
|---|---|---|---|---|---|---|---|
| 1 | Pourmohammadi et al. | 2008 | Single | Multi | GA | Environmental | Design and planning |
| 2 | Kannan et al. | 2009 | Multi | Single | GA and PSO | Environmental | Planning |
| 3 | Paksoy et al. | 2011 | Multi | Single | LINDO | Environmental | Planning and transportation |
| 4 | Kannan et al. | 2012 | Single | Single | LINGO | Environmental | Design |
| 5 | Qiang et al. | 2013 | Single | Single | Analytical | Environmental | planning |
| 6 | Entezaminia et al. | 2016 | Multi | Single | CPLEX | Environmental | Planning |
| 7 | Zohal and Soleimani | 2016 | Single | Multi | Ant colony optimization using LINGO | Environmental | Design and planning |
| 8 | Kumar et al. | 2017 | Single | Single | Artificial Immune System and PSO | Environmental | Design and planning |
| 9 | **This paper** | **2017** | **Multi** | **Multi** | **GAMS- Epsilon-constraint method** | **Environmental** | **Design and planning** |

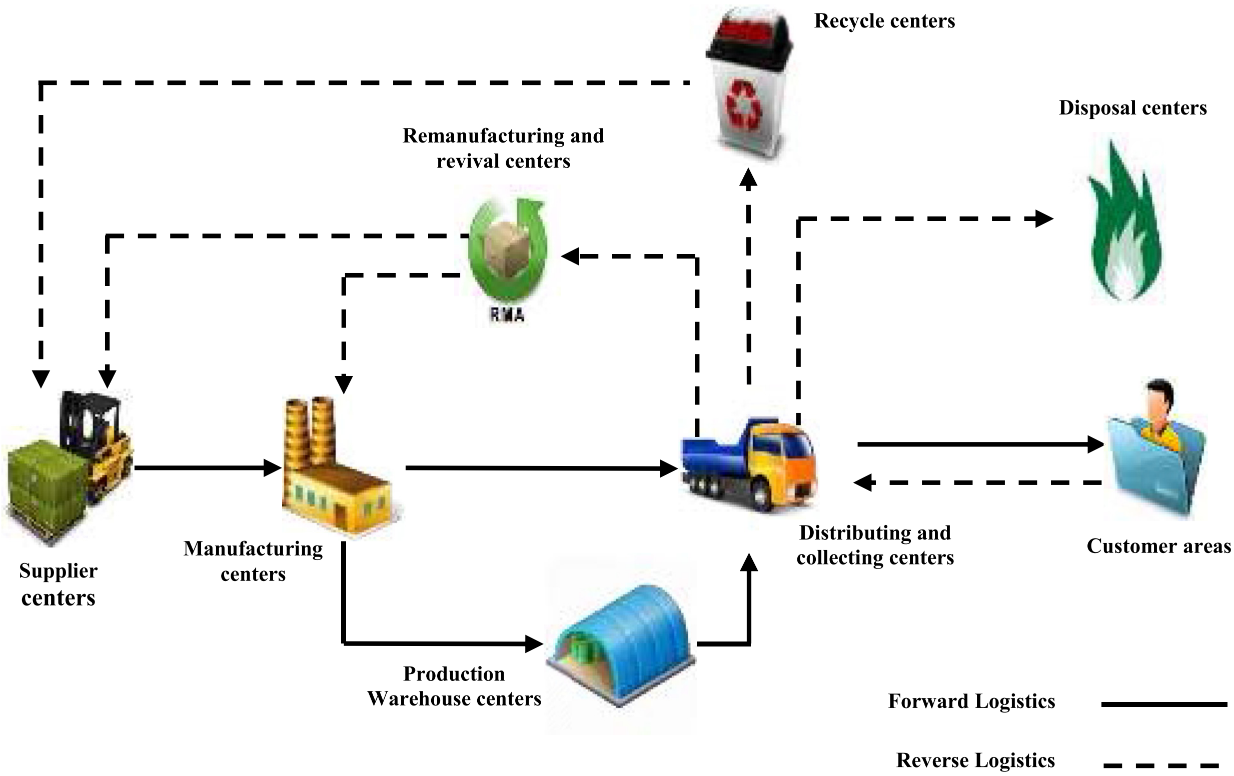


**Fig. 3.** Flow of forward and reverse logistics activities.

- The quality of the recovered products differs from the quality of the new products.
- The cost of transporting the raw material is the same as the cost of transporting the products.
- While the location of sale of the recovered and new products are the same, the model considers only one type of customer.
- The number of supplier centers, manufacturing centers, warehouses, and customer areas are known and fixed. The number of other centers is also known.
- The distribution and collection centers for the new and returned products are integrated because both forward and reverse logistics are considered simultaneously.
- The sum of the returned products coefficients equals to 1, as the parameters used as the rate of the returned products are coefficients. The four flows are structured as a mutually exclusive set.

### 3.3. Indices

Table 2 presents the indices used in the model.

**Table 2**
Indices of green forward and reverse logistics model.

| Indices and sets | Definition |
|---|---|
| $(i\in I)$ | Index of supplier centers $(i)$ |
| $(j\in J)$ | Index of manufacturing centers $(j)$ |
| $(m\in M)$ | Index of distribution and collection centers $(m)$ |
| $(l\in L)$ | Index of customer areas $(l)$ |
| $(k\in K)$ | Index of remanufacturing and revival centers $(k)$ |
| $(p\in P)$ | Index of recycling centers $(p)$ |
| $(n\in N)$ | Index of disposal centers $(n)$ |
| $(s\in S)$ | Index of products $(s)$ |

### 3.4. Parameters

Table 3 shows the parameters used in the model.

### 3.5. Variables

Table 4 shows the variables used in the model.

### 3.6. Mathematical model

The mathematical representation of the model is presented as follows:

$$\begin{aligned}
\text{Min } Z_1 = {} & \sum_{m\in M} f_m Z_m + \sum_{k\in K} f_k Z_k + \sum_{p\in P} f_p Z_p + \sum_{n\in N} f_n Z_n \\
& + \sum_{s\in S}\sum_{i\in I}\sum_{j\in J} c^s_{ij} Y^s_{ij} + \sum_{s\in S}\sum_{j\in J}\sum_{m\in M} c^s_{jm} Y^s_{jm} + \sum_{s\in S}\sum_{j\in J} cq^s_{jj} X^s_{jj} \\
& + \sum_{s\in S}\sum_{m\in M}\sum_{l\in L} c^s_{ml} Y^s_{ml} + \sum_{s\in S}\sum_{j\in J}\sum_{m\in M} cq^s_{jm} X^s_{jm} \\
& + \sum_{s\in S}\sum_{l\in L}\sum_{m\in M} c^s_{lm} Y^s_{lm} + \sum_{s\in S}\sum_{m\in M}\sum_{k\in K} c^s_{mk} Y^s_{mk} \\
& + \sum_{s\in S}\sum_{k\in K}\sum_{j\in J} c^s_{kj} Y^s_{kj} + \sum_{s\in S}\sum_{m\in M}\sum_{n\in N} c^s_{mn} Y^s_{mn} \\
& + \sum_{s\in S}\sum_{m\in M}\sum_{p\in P} c^s_{mp} Y^s_{mp} + \sum_{s\in S}\sum_{p\in P}\sum_{i\in I} c^s_{pi} Y^s_{pi} \\
& + \sum_{s\in S}\sum_{k\in K}\sum_{i\in I} c^s_{ki} Y^s_{ki} + \sum_{s\in S}\sum_{j\in J} h^s_j Q^s_j
\end{aligned} \tag{1}$$

**Table 3**
Parameters of green forward and reverse logistics model.

| Parameter | Definition |
|---|---|
| $d_l^s$ | Demand of product *s* in customer area *l* |
| $d_n^s$ | Demand of product *s* in disposal center *n* |
| $d_p^s$ | Demand of product *s* in recycling center *p* |
| $d_k^s$ | Demand of product *s* in remanufacturing and revival center *k* |
| $r_l^s$ | Number of returned used product *s* from customer area *l* |
| $B_l^s$ | Rate of product *s* from distribution and collection center *m* to customer area *l* |
| $B_k^s$ | Rate of return of used product *s* from distribution and collection center *m* to remanufacturing and revival center *k* |
| $B_p^s$ | Rate of return of used product *s* from distribution and collection center *m* to recycling center *p* |
| $B_n^s$ | Rate of return of used product *s* from distribution and collection center *m* to disposal center *n* |
| $f_m$ | Fixed costs of establishing distribution and collection center *m* |
| $f_k$ | Fixed costs of establishing remanufacturing and revival center *k* |
| $f_p$ | Fixed costs of establishing recycling center *p* |
| $f_n$ | Fixed costs of establishing disposal center *n* |
| $c_{ij}^s$ | Cost of processing and transporting a unit of product *s* from supplier center *i* to manufacturing center *j* |
| $c_{jm}^s$ | Cost of processing and transporting a unit of product *s* from manufacturing center *j* to distribution and collection center *m* |
| $cq_{jj}^s$ | Cost of processing and transporting a unit of product *s* from manufacturing center *j* to its warehouse *j* |
| $c_{ml}^s$ | Cost of processing and transporting a unit of product *s* from distribution and collection center *m* to customer area *l* |
| $cq_{jm}^s$ | Cost of processing and transporting a unit of product *s* from warehouse of manufacturing center *j* to distribution and collection center *m* |
| $c_{lm}^s$ | Cost of processing and transporting a unit of returned used product *s* from customer area *l* to distribution and collection center *m* |
| $c_{mk}^s$ | Cost of processing and transporting a unit of returned used product *s* from distribution and collection center *m* to remanufacturing and revival center *k* |
| $c_{mn}^s$ | Cost of processing and transporting a unit of returned used product *s* from distribution and collection center *m* to disposal center *n* |
| $c_{mp}^s$ | Cost of processing and transporting a unit of returned used product *s* from distribution and collection center *m* to recycling center *p* |
| $c_{kj}^s$ | Cost of processing and transporting a unit of recovered product *s* from remanufacturing and revival center *k* to manufacturing center *j* |
| $c_{pi}^s$ | Cost of processing and transporting a unit of raw material *s* from recycling center *p* to supplier center *i* |
| $c_{ki}^s$ | Cost of processing and transporting a unit of recovered product *s* from remanufacturing and revival center *k* to supplier center *i* |
| $CO2_{ij}^s$ | Amount of $CO_2$ emission for a unit of product *s* from supplier center *i* to manufacturing center *j* [g] |
| $CO2_{jm}^s$ | Amount of $CO_2$ emission for a unit of product *s* from manufacturing center *j* to distribution and collection center *m* [g] |
| $CO2_{ml}^s$ | Amount of $CO_2$ emission for a unit of product *s* from distribution and collection center *m* to customer area *l* [g] |
| $CO2_{lm}^s$ | Amount of $CO_2$ emission for a unit of returned used product *s* from customer area *l* to distribution and collection center *m* [g] |
| $CO2_{mk}^s$ | Amount of $CO_2$ emission for a unit of returned used product *s* from distribution and collection center *m* to remanufacturing and revival center *k* [g] |
| $CO2_{mn}^s$ | Amount of $CO_2$ emission for a unit of returned used product *s* from distribution and collection center *m* to disposal center *n* [g] |
| $CO2_{mp}^s$ | Amount of $CO_2$ emission for a unit of returned used product *s* from distribution and collection center *m* to recycling center *p* [g] |
| $CO2_{kj}^s$ | Amount of $CO_2$ emission for a unit of recovered product *s* from remanufacturing and revival center *k* to manufacturing center *j* [g] |
| $CO2_{pi}^s$ | Amount of $CO_2$ emission for a unit of raw material *s* from recycling center *p* to supplier center *i* [g] |
| $CO2_{ki}^s$ | Amount of $CO_2$ emission for a unit of recovered product *s* from remanufacturing and revival center *k* to supplier center *i* [g] |
| $h_j^s$ | Cost of stocking a unit of product *s* in warehouse of manufacturing center *j* |
| $g_i$ | Capacity of supplier center *i* |
| $g_j$ | Capacity of manufacturing center *j* |
| $g_{jj}$ | Capacity of warehouse of manufacturing center *j* |
| $g_m$ | Capacity of distribution and collection center *m* for new products |
| $gr_m$ | Capacity of distribution and collection center *m* for recovered products |
| $g_k$ | Capacity of remanufacturing and revival center *k* |
| $g_n$ | Capacity of disposal center *n* |
| $g_p$ | Capacity of recycling center *p* |
| $\upsilon_m$ | Number of machines in production line used in distribution and collection center *m* |
| $\upsilon_k$ | Number of machines in production line used in remanufacturing and revival center *k* |
| $\upsilon_n$ | Number of machines in production line used in disposal center *n* |
| $\upsilon_p$ | Number of machines in production line used in recycling center *p* |

$$\begin{aligned}\text{Min } Z_2 = & \sum_{s\in S}\sum_{i\in I}\sum_{j\in J} Y_{ij}^s CO2_{ij}^s + \sum_{s\in S}\sum_{j\in J}\sum_{m\in M} Y_{jm}^s CO2_{jm}^s \\ & + \sum_{s\in S}\sum_{m\in M}\sum_{l\in L} Y_{ml}^s CO2_{ml}^s + \sum_{s\in S}\sum_{l\in L}\sum_{m\in M} Y_{lm}^s CO2_{lm}^s \\ & + \sum_{s\in S}\sum_{m\in M}\sum_{k\in K} Y_{mk}^s CO2_{mk}^s + \sum_{s\in S}\sum_{k\in K}\sum_{j\in J} Y_{kj}^s CO2_{kj}^s \\ & + \sum_{s\in S}\sum_{m\in M}\sum_{n\in N} Y_{mn}^s CO2_{mn}^s + \sum_{s\in S}\sum_{m\in M}\sum_{p\in P} Y_{mp}^s CO2_{mp}^s \\ & + \sum_{s\in S}\sum_{p\in P}\sum_{i\in I} Y_{pi}^s CO2_{pi}^s + \sum_{s\in S}\sum_{k\in K}\sum_{i\in I} Y_{ki}^s CO2_{ki}^s \end{aligned} \tag{2}$$

$$\text{Min } Z_3 = \sum_{m\in M} \upsilon_m Z_m + \sum_{k\in K} \upsilon_k Z_k + \sum_{n\in N} \upsilon_n Z_n + \sum_{p\in P} \upsilon_p Z_p \tag{3}$$

According to Eqs. (1)–(3), a model with three objective functions is provided. The first is to optimize the fixed costs of establishing as well as the costs of the operations, processing, and transportation (see Eq. (1)). The second objective function is to optimize the amount of $CO_2$ in all the forward and reverse logistics network flows (see Eq. (2)). The third objective function is to optimize the number of machines in the production lines which consist of four terms; the first term optimizes the number of machines in the production line used in the distribution and collection centers, and the second term is the machines used in the remanufacturing and revival centers. The third and fourth terms are minimizing the number of machines in the production line that are

**Table 4**
Variables of green forward and reverse logistics model.

| Variable | Definition |
|---|---|
| $Y_{ij}^s$ | Quantity transported from supplier center *i* to manufacturing center *j* |
| $Y_{jm}^s$ | Quantity transported from manufacturing center *j* to distribution and collection center *m* |
| $X_{jj}^s$ | Quantity transported from manufacturing center *j* to its warehouse *j* |
| $Y_{ml}^s$ | Quantity transported from distribution and collection center *m* to customer area *l* |
| $X_{jm}^s$ | Quantity transported from warehouse of manufacturing center *j* to distribution and collection center *m* |
| $Y_{lm}^s$ | Quantity transported from customer area *l* to distribution and collection center *m* |
| $Y_{mk}^s$ | Quantity transported from distribution and collection center *m* to remanufacturing and revival center *k* |
| $Y_{mn}^s$ | Quantity transported from distribution and collection center *m* to disposal center *n* |
| $Y_{mp}^s$ | Quantity transported from distribution and collection center *m* to recycling center *p* |
| $Y_{kj}^s$ | Quantity transported from remanufacturing and revival center *k* to manufacturing center *j* |
| $Y_{pi}^s$ | Quantity transported from recycling center *p* to supplier center *i* |
| $Y_{ki}^s$ | Quantity transported from remanufacturing and revival center *k* to supplier center *i* |
| $Q_j^s$ | Quantity of product *s* in warehouse of manufacturing center *j* |
| $Z_m$ | $\begin{cases} 1 & \text{if distribution and collection center } m \text{ is established} \\ 0 & \text{otherwise} \end{cases}$ |
| $Z_k$ | $\begin{cases} 1 & \text{if remanufacturing and revival center } k \text{ is established} \\ 0 & \text{otherwise} \end{cases}$ |
| $Z_n$ | $\begin{cases} 1 & \text{if disposal center } n \text{ is established} \\ 0 & \text{otherwise} \end{cases}$ |
| $Z_p$ | $\begin{cases} 1 & \text{if recycling center } p \text{ is established} \\ 0 & \text{otherwise} \end{cases}$ |

used in the disposal and recycle centers respectively (see Eq. (3)). In addition, the associated constraints are presented in Eqs. (4)–(31).

Subject to

$$\sum_{m\in M} Y_{ml}^s = d_l^s \quad \forall l\in L, s\in S \tag{4}$$

$$\sum_{m\in M} Y_{lm}^s = r_l^s \quad \forall l\in L, s\in S \tag{5}$$

Constraints 4 and 5 guarantee that, in forward logistics, all the customer demands are accepted and satisfied, and, in reverse logistics, all the returned used products from the customer centers are collected. Therefore, the demands of the customers ($d_l^s$) and the number of returned used product ($r_l^s$) should be equal to the product flows from the distribution and collection centers to the customers ($Y_{ml}^s$) and the product flows from customers to the distribution and collection centers ($Y_{lm}^s$). With more goods returned and collected from the customers in an effective reverse logistics network, the more profit can the companies make.

$$\sum_{m\in M} Y_{mn}^s \le d_n^s \quad \forall n\in N, s\in S \tag{6}$$

$$\sum_{m\in M} Y_{mp}^s \le d_p^s \quad \forall p\in P, s\in S \tag{7}$$

$$\sum_{m\in M} Y_{mk}^s \le d_k^s \quad \forall k\in K, s\in S \tag{8}$$

Constraints 6 to 8 limit the amount of the demands of the reverse logistics centers compared to their input flows. Since the products should be sent to the disposal, recycle, and remanufacturing and revival centers based on the demands of the centers mentioned, the demands of these centers should always be greater than or equal to the input product flows.

$$\sum_{k\in K} Y_{mk}^s = B_k^s \sum_{l\in L} Y_{lm}^s \quad \forall m\in M, s\in S \tag{9}$$

$$\sum_{p\in P} Y_{mp}^s = B_p^s \sum_{l\in L} Y_{lm}^s \quad \forall m\in M, s\in S \tag{10}$$

$$\sum_{n\in N} Y_{mn}^s = B_n^s \sum_{l\in L} Y_{lm}^s \quad \forall m\in M, s\in S \tag{11}$$

$$\sum_{j\in J} \left(Y_{jm}^s + X_{jm}^s\right) = \sum_{l\in L} Y_{ml}^s \quad \forall m\in M, s\in S \tag{12}$$

$$\sum_{i\in I} Y_{ij}^s + \sum_{k\in K} Y_{kj}^s = \sum_{m\in M} Y_{jm}^s + X_{jj}^s \quad \forall j\in J, i\in I, s\in S \tag{13}$$

$$\sum_{k\in K} Y_{ki}^s + \sum_{p\in P} Y_{pi}^s \le \sum_{j\in J} Y_{ij}^s \quad \forall i\in I, s\in S \tag{14}$$

Constraints 9 to 14 are the balance constraints which demonstrate the conservation of flows at the junctions. In short, for a balanced network, the input and output flows of the nodes should be conserved. Thus, these constraints are equalities between the input and output flows.

$$Q_j^s = X_{jj}^s - \sum_{m\in M} X_{jm}^s \quad \forall j\in J, s\in S \tag{15}$$

Constraint 15 speaks to the remaining inventory in the warehouses of the manufacturing centers. It assures that the out of the stock product flows of the manufacturers is less than the entry of goods into the manufacturer's warehouses. As a consequence, the stock in the warehouse is equal to input product flows less the output product flows to the distribution and collection centers.

$$\sum_{m\in M} X_{jm}^s \le X_{jj}^s \quad \forall j\in J, s\in S \tag{16}$$

Constraint 16 guarantees that the amount of output flows from the warehouses of the manufacturing centers is less than the amounts of their input flows. This constraint is directly related to the stock in the warehouses because if the input flow is less than the output flow, there would not be any product in the warehouse and all the products can be cross docked.

$$\sum_{s\in S}\sum_{j\in J}Y^s_{ij} \le g_i \quad \forall i\in I \tag{17}$$

$$\sum_{s\in S}\sum_{m\in M}Y^s_{jm} + \sum_{s\in S}X^s_{jj} \le g_j \quad \forall j\in J \tag{18}$$

$$\sum_{s\in S}\sum_{l\in L}Y^s_{ml}B^s_l + \sum_{s\in S}\sum_{k\in K}Y^s_{mk}B^s_k + \sum_{s\in S}\sum_{n\in N}Y^s_{mn}B^s_n + \sum_{s\in S}\sum_{p\in P}Y^s_{mp}B^s_p \le g_m Z_m \quad \forall m\in M \tag{19}$$

$$\sum_{s\in S}\sum_{l\in L}Y^s_{ml}B^s_l \le gr_m Z_m \quad \forall m\in M \tag{20}$$

$$\sum_{s\in S}\sum_{m\in M}Y^s_{mk} \le g_k Z_k \quad \forall k\in K \tag{21}$$

$$\sum_{s\in S}\sum_{m\in M}Y^s_{mn} \le g_n Z_n \quad \forall n\in N \tag{22}$$

$$\sum_{s\in S}\sum_{m\in M}Y^s_{mp} \le g_p Z_p \quad \forall p\in P \tag{23}$$

$$\sum_{s\in S}Q^s_j \le g_{jj} \quad \forall j\in J \tag{24}$$

Constraints 17 to 24 assure that a center has been established only between the areas where a flow exists, and that the total flows to and from each center could not exceed its capacity. These constraints ensure that flow is kept just between the points where there are facilities, and the total flow at each facility must not exceed the capacity of that facility.

$$\sum_{m\in M}Z_m \ge 1 \tag{25}$$

$$\sum_{k\in K}Z_k \ge 1 \tag{26}$$

$$\sum_{p\in P}Z_p \ge 1 \tag{27}$$

$$\sum_{n\in N}Z_n \ge 1 \tag{28}$$

Constraints 25 to 28 guarantee that at least one of the potential centers must be activated. The importance of these constraints is that if one of the set of centers is completely deactivated, the network would be deactivated. Consequently, the decision variables for establishing the centers should always be greater than or equal to one.

$$Y^s_{ij}, Y^s_{jm}, X^s_{jj}, Y^s_{ml}, X^s_{jm}, Y^s_{lm}, Y^s_{mk}, Y^s_{kj}, Y^s_{mn}, Y^s_{mp}, Y^s_{pi}, Y^s_{ki}, Q^s_j \ge 0 \quad \forall i,j,m,l,k,n,p,\ s \tag{29}$$

$$Z_m, Z_k, Z_p, Z_n = \{0,1\} \quad \forall m,k,p,n \tag{30}$$

Finally, constraints 29 and 30 are the non-negativity and binary restrictions on the decision variables, representing the type of decision variables of the problem.

## 4. Solution method

The aim of developing a multi-objective optimization problem is to optimize several objective functions simultaneously. Clearly, optimizing just one objective function is easier albeit less practical than multi-objective optimization (Hiremath et al., 2013). Indeed, there is more than one conflicting objective function in most multi-objective problems (Mavrotas, 2009). Additionally, in a multi-objective approach, each objective function has its peculiar goal (Aghaei et al., 2011). It should be mentioned that there are two classes of methods to optimize the presented multi-objective model: the first one is using meta-heuristics or evolutionary methods which can yield acceptable solutions. However, the quality of the solutions and their optimality are not known. The other type of methods is the exact or heuristic methods used to pbtain the Pareto solutions. In this study, the latter (exact) method, an epsilon-constraint approach, is applied to solve the model. To validate the model and the proposed solution approach, three types of numerical instances associated with a case study in the home appliance industry are provided, the solution technique (epsilon-constraint method) as well as sensitivity analysis are developed in GAMS ver. 25.1.2. All the instances are solved on a PC with Intel core i5 CPU and 4 GB RAM.

### 4.1. Epsilon-constraint method

The epsilon-constraint method is a popular method to handle multi-objective optimization. This technique solves the model in a repetitively in which in each step all the objective functions, except one, are converted to appropriate epsilon-based constraints (Hwang and Masud, 1979). Indeed, for any multi-objective model, the following holds (see Eq. (31)):

$$\min\Big(f_1(x), f_2(x), \ldots, f_p(x)\Big) \tag{31}$$

subject to

$x\in S$.

In this approach, for each replication, one objective function is taken as the only objective function while the others are set as constraints using appropriate epsilons (see Eq. (32)) (Mavrotas, 2009) i.e.

$$\min f_1(x) \tag{32}$$

subject to

$f_2(x) \le \varepsilon_2$

$f_3(x) \le \varepsilon_3$

…

$f_p(x) \le \varepsilon_p$

$x\in S$.

The solutions on the Pareto frontier in the multi-objective models are a set of non-dominated solutions. Ultimately, the decision-maker choose the best solution with respect to their goal and the Pareto solutions (Khalili-Damghani et al., 2013). The proposed epsilon-constraint model of this paper is represented as follows:

**Table 5**
Values of epsilons and results of objective functions.

| $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_2$ | $\varepsilon_3$ | $Z_1$ [100,000 Rials] | $Z_2$ [g] | $Z_3$ [No. of machines] |
|---|---|---|---|---|---|---|
| $0.75*\alpha+\alpha$ | $0.9*\beta+\beta$ | 11831.55 | 42 | 29177.86 | 11659.66 | 35 |
| $0.7*\alpha+\alpha$ | $0.8*\beta+\beta$ | 11550.6 | 39.9 | 29205.69 | 11550.6 | 35 |
| $0.65*\alpha+\alpha$ | $0.7*\beta+\beta$ | 11269.65 | 37.8 | 29298.37 | 11269.65 | 35 |
| $0.6*\alpha+\alpha$ | $0.6*\beta+\beta$ | 10988.7 | 35.7 | 29553.92 | 10988.71 | 35 |
| $0.55*\alpha+\alpha$ | $0.5*\beta+\beta$ | 10707.76 | 33.6 | 30155.69 | 10707.76 | 30 |
| $0.5*\alpha+\alpha$ | $0.4*\beta+\beta$ | 10426.81 | 31.5 | 30612.72 | 10426.81 | 30 |
| $0.45*\alpha+\alpha$ | $0.35*\beta+\beta$ | 10145.86 | 29.4 | 31683.35 | 10145.86 | 28 |
| $0.45*\alpha+\alpha$ | $0.3*\beta+\beta$ | 9958.56 | 28 | 32117.01 | 9958.56 | 28 |
| $0.4*\alpha+\alpha$ | $0.25*\beta+\beta$ | 9864.91 | 27.3 | 34053.92 | 9864.91 | 23 |
| $0.4*\alpha+\alpha$ | $0.2*\beta+\beta$ | 9771.2 | 26.6 | 34615.51 | 9771.2 | 23 |

**Table 6**
Dimensions of test problems.

| Index | Small-Size | Medium-Size | Large-Size |
|---|---|---|---|
| ***I*** | 1 | 2 | 2 |
| ***J*** | 1 | 2 | 4 |
| ***M*** | 2 | 2 | 3 |
| ***L*** | 3 | 3 | 10 |
| ***K*** | 1 | 2 | 2 |
| ***P*** | 2 | 2 | 2 |
| ***N*** | 1 | 1 | 1 |
| ***S*** | 2 | 3 | 2 |

$$\text{Min } Z_1 \tag{33}$$

subject to

$$Z_2 \le \varepsilon_2$$

$$Z_3 \le \varepsilon_3$$

and Constraints 4 to 30.

The presented model in Eq. (33) is solved for the following two situations:

- With $Z_2$ as the objective function and eliminating $Z_1$ and $Z_3$ to find the optimum value of $Z_2$ which is termed as $\alpha$ here.
- With $Z_3$ as the objective function and eliminating $Z_1$ and $Z_2$ to find the optimum value of $Z_3$ which is termed as $\beta$ here.

To find the Pareto optimal solutions, the epsilons associated with $Z_2$ and $Z_3$ are assigned based on the values of $\alpha$ and $\beta$, which are 6831.23 g of $CO_2$ and 22 machines respectively. The values related to the epsilons are illustrated in Table 5.

From Table 5, clearly $\varepsilon_2 \in (9022.07,\ 11831.55)$ and $\varepsilon_3 \in (21,\ 42)$. In each instance of Table 5, the three objective functions might lead to a Pareto solution and the final computations can present a schematic of the Pareto frontier and likewise for the non-dominated solutions. The details of the numerical validation of the model and the solution methodology are discussed next.

## 5. Numerical experimentation

In this section, several test problems of different sizes (small, medium, large) are generated based on an actual case study and the model is solved using the above solution approach. Following this, a sensitivity analysis is performed on the objective function values. To validate the proposed model, the model is applied on SAMSUM,[1] a home appliance company in Iran. Further, to evaluate the efficiency and performance of the model such that all size of firms can be addressed, three types of test problems of various sizes (small, medium, large) are considered, drawing from sample data provided by the case firm SAMSUM. Table 6 shows the dimensions of the instances. Table 7 shows the model parameters of the numerical experiments.

The parameters are fixed for all the test problems while the size of the instances are increased. For instance, when a center is added to a network, its demand, capacity, fixed cost of establishment and other related parameters are determined through Table 7. However, the number of facilities increases, so the instance becomes harder to solve. Further, as Iranian firms are only starting to manage $CO_2$ emissions, so the parameters of the $CO_2$ emission are estimated based on the experts' idea of the mentioned company and industry norms. The computational results of the model found through the epsilon-constraint method are presented in the next section.

## 6. Results and discussion

Three sets of Pareto solutions are found through the epsilon-constraint method on the test problems as shown in Tables 8–10, which show the objective values of the test problems. For ease of visualisation, a three-dimensional diagram is designed to illustrate the Pareto frontier of the value of the objective functions for each size of the test problem as shown in Fig. 4. The optimality gap in this study is zero as that the model is linear and GAMS can solve it exactly. Also, the number of variables for the small-size test problems is 68 with computational time of 15 s. For the medium-sized instances, there are 163 variables with 22 s as computational time. Finally, model is solved with 294 variables and approximately 31 s of computational time for the large-size test problems.

As can be seen from Table 8, $Z_1$ for the small-size test problems shows a monotone increasing behaviour, while $Z_2$ and $Z_3$ are oscillatory. For the medium-size test instances in Table 9, $Z_1$ is concave. As for $Z_2$ and $Z_{3,}$ the behaviour is somewhat oscillatory. For the large-size test problems, Table 10 shows $Z_1$ to be monotone increasing and oscillatory patterns for $Z_{2,}$ and $Z_3$.

From Fig. 4 and the values of Tables 8–10, it is clear that improving the value of the first objective function, leads to a worsening of the values of the other two objective functions. In short, the objective functions are in conflict with each other. Further, Fig. 4(a) suggests that the distance between the ideal point and the Pareto solutions is more than the other sizes of test problem which is diminished for the medium-size test problem Fig. 4(b). Nonetheless, the Pareto solutions are close to the ideal point on the large-size test problem. Consequently, the proposed method could lead to better results when applied to large-sized problems.

Fig. 5 highlights the values of the objective functions of the test

[1] www.samsum.co.ir.

**Table 7**
Value of parameters in the test problems.

| Parameter | Value |
|---|---|
| Demand of product in customer area | 30 |
| Demand of product in remanufacturing and revival centers | 10 |
| Demand of product in disposal centers | 8 |
| Demand of product in recycling centers | 12 |
| Capacity for products in supplier centers | 65 |
| Capacity for products in manufacturing centers | 100 |
| Capacity for products in warehouse centers | 45 |
| Capacity for products in distribution and collection centers for new products | 65 |
| Capacity for products in distribution and collection centers | 45 |
| Capacity for products in remanufacturing and revival centers | 55 |
| Capacity for products in disposal centers | 55 |
| Capacity for products in recycling centers | 60 |
| Fixed costs of establishment | 320 [mil. Rials] |
| Amount of $CO_2$ emission for a unit of product | 1.5 [g] |
| Number of machines in production line in distribution and collection centers | 5 |
| Number of machines in production line in remanufacturing and revival centers | 4 |
| Number of machines in production line in disposal centers | 3 |
| Number of machines in production line in recycling centers | 4 |

**Table 8**
Objective function values for small-sized test problem.

| Solution | $Z_1$ [mil. Rials] | $Z_2$ [g] | $Z_3$ [No. of machines] |
|---|---|---|---|
| 1 | 8519.35 | 2942.34 | 23 |
| 2 | 8535.11 | 2901.69 | 23 |
| 3 | 8541.22 | 2940.13 | 21 |
| 4 | 8576.90 | 2820.39 | 23 |
| 5 | 8891.57 | 2657.92 | 18 |
| 6 | 8891.57 | 2655.71 | 16 |
| 7 | 9833.72 | 2535.84 | 26 |

**Table 9**
Objective function values for medium-sized test problem.

| | | | |
|---|---|---|---|
| 1 | 12807.05 | 4797.74 | 18 |
| 2 | 12836.58 | 4743.2 | 18 |
| 3 | 13745.17 | 4665.94 | 15 |
| 4 | 13746.21 | 4665.94 | 14 |
| 5 | 13792.34 | 4588.68 | 14 |
| 6 | 14232.67 | 4897.73 | 13 |
| 7 | 14245.98 | 4820.47 | 13 |
| 8 | 13588.58 | 4279.64 | 18 |
| 9 | 16091.42 | 4125.11 | 26 |
| 10 | 13209.13 | 4434.16 | 18 |

**Table 10**
Objective function values for large-sized test problem.

| | | | |
|---|---|---|---|
| 1 | 29177.87 | 11659.67 | 35 |
| 2 | 29205.69 | 11550.61 | 35 |
| 3 | 29298.37 | 11269.66 | 35 |
| 4 | 29510.25 | 11269.66 | 30 |
| 5 | 29553.92 | 10988.71 | 35 |
| 6 | 29774.11 | 11831.55 | 28 |
| 7 | 30349.82 | 11780.06 | 23 |
| 8 | 30486.99 | 10988.71 | 28 |
| 9 | 30612.7 | 10426.8 | 30 |
| 10 | 30805.22 | 10707.76 | 28 |
| 11 | 32403.64 | 11831.55 | 21 |
| 12 | 32660.57 | 11550.61 | 21 |
| 13 | 34986.73 | 9303.02 | 30 |
| 14 | 38488.12 | 9022.07 | 42 |

problems. Here, the values of each objective function with the three sizes of instances are shown. In the first part of Fig. 5 (small and medium sizes), by increasing the amount of instances, the oscillations of the values of the first objective function is attenuated. However, in the larger instances, the value of the first objective function increases as well as the costs of the operations, processes, transportation, and the fixed costs of the establishment. In the second part, in the large sized sample problem, the value of the second objective function is decreased, while in the small and medium sized sample problems, there are no changes in the amount of $CO_2$ emissions in all instances. Moreover, on the third objective function, more oscillations can be seen with increasing number of sample problems. Next, from Fig. 5, it appears that behaviour of Z1, Z2, Z3 become more erratic as the size of the test problem increases and the number of test solutions increases. This is particularly so for the number of machines used.

## 7. Sensitivity analysis

In order to explore the changes in the values of the objective functions based on the parameters, a sensitivity analysis could be applied on the main parameters. Since the model is multi-objective, there are two types of analyses: In the first type, the changes of the Pareto values (set of Pareto solutions) are explored based on the changes in demand as the main parameter of the model. The analyses are undertaken for the medium-sized instances. The changes in the demands are illustrated in Table 11. The results of the sensitivity analysis, based on the changes in demand, are demonstrated in Table 12.

Tables 11 and 12 can support the normal and appropriate behaviour of the model to demand changes in that by changing the demand, the values of the objective functions are increased to reach a peak in the test problems before decreasing. For example, $Z_1$ in test problem 1 is 14067.75 which peaks at 16815.57 in test problem 9, and then reduces to 14172.14 in test problem 10. Likewise, $Z_2$ increases to 7559 in test problem 8 and then drops to 5174.18 in test problem 10. These trend are consistent with the change in demand patterns set in Table 11. Hence, it can validate the model and solution method work correctly.

Similarly, in the sensitivity analysis on the Pareto values, based on the cost parameter and the rate of return of the used products, one of the Pareto solutions is explored. The values $Z_1$ are presented in Fig. 6 and Fig. 7 associated with the variations in the processing and transportation costs as well as the rate of return of the used products respectively.

From Fig. 6, as expected, as the average processing and transportation costs increase, $Z_1$ (holding the other objective functions as constraints) increases as well.

From Fig. 7, by increasing the rate of return of the used products,

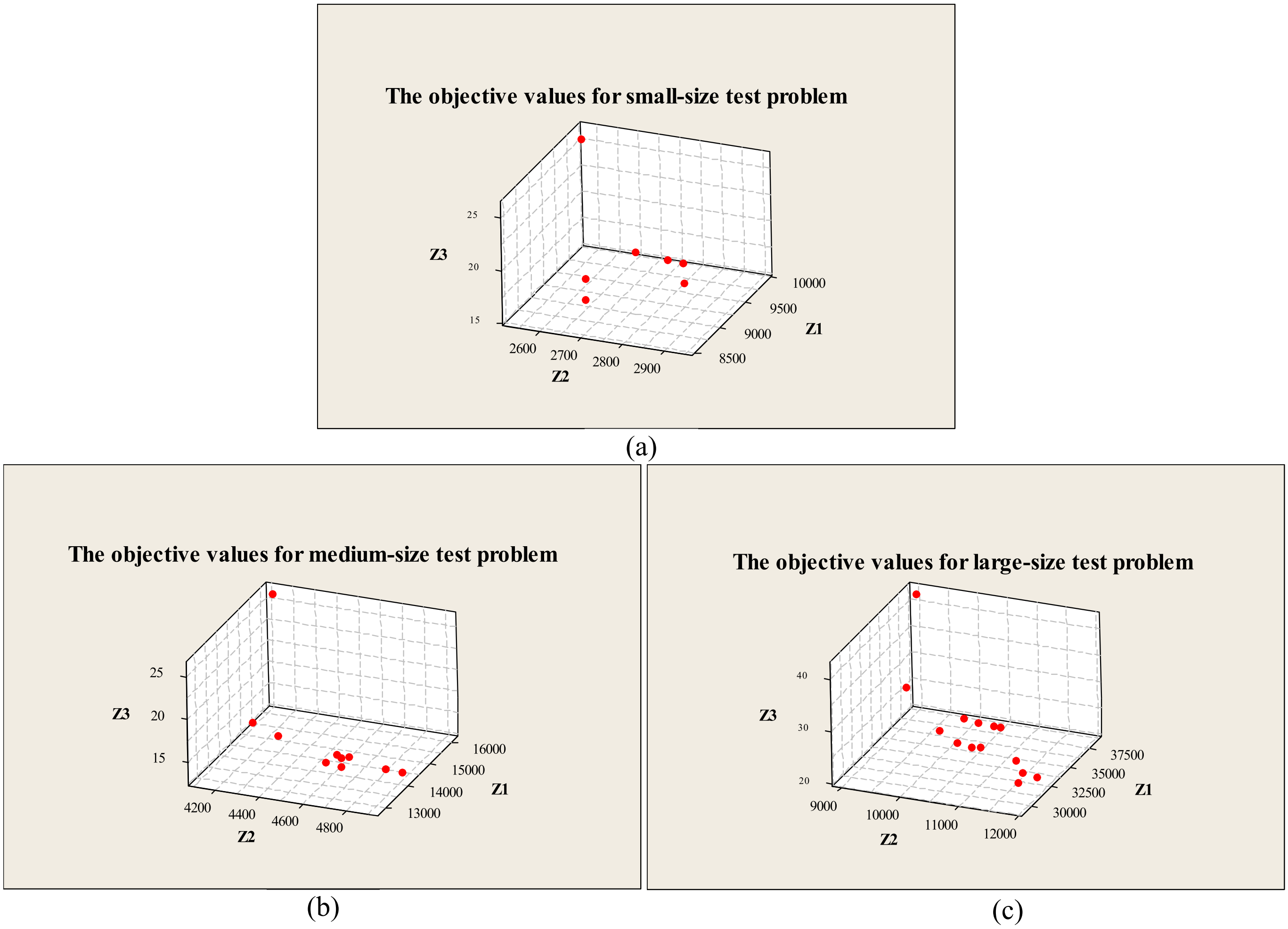


**Fig. 4.** 3-D of Pareto solutions for (a) small, (b) medium size, and (c) large sized problem.

$Z_1$ holding the other objective functions as constraints) increases too. Clearly, $Z_1$ increases with the rising processing cost from the supplier centers to the manufacturing centers (Fig. 6), and with the average return rate of the used products from the distribution and collection centers to the remanufacturing and revival centers (Fig. 7).

## 8. Managerial implications

The most significant managerial implication of this research is related to the case study of a company in the home appliance industry. The outcomes can be used by managers and decision-makers to reduce their total costs and lessen the amount of emitted $CO_2$ to protect the environment. Doing so will not only help them to sustain competitive advantage in the current market, but also to better plan for the future. The findings of this study can also assist the manufacturing companies in other industries in their decision-making processes. Companies could use our model and method to optimally manage their cost and emissions throughout their supply chains. At the same time, the government instruments which are responsible for economic and environmental matters can use the sensitivity analysis to introduce suitable and robust legislations on business in an objective manner when dealing with reverse logistics activities, costs, and flows.

## 9. Conclusion and future research

This paper focuses on the minimization of the costs of transportation, processing, and establishment while regarding reducing the amount of $CO_2$ emissions and decreasing the number of machines in the production lines. This study presents a multi-stage, multi-product, multi-objective model to plan, design, and optimize a forward and reverse logistics network, seeking to plug the gap in the existing body of research. We develop a novel multi-objective model with two economic objectives ($Z_1$ and $Z_3$) as well as an environmental objective ($Z_2$), with the model considering both forward and reverse logistics flows of products integrally. This treatment is new in the literature. Further, an epsilon-constraint method is developed and fitted to the proposed model to extract the value of the objective functions.

The results of epsilon-constraint method obtained the Pareto frontier of the objective functions. Then, the model is applied to the home appliance industry and we generated three types of test problems (small, medium, and large). The model with the test problems was coded in GAMS to yield the set of Pareto solutions. Finally, we used sensitivity analysis on the model to analyse the effect of variations in the demand, costs, and rate of return of the used products on the objective functions. Specifically, we find that lowering the total cost (including the number of machines to be

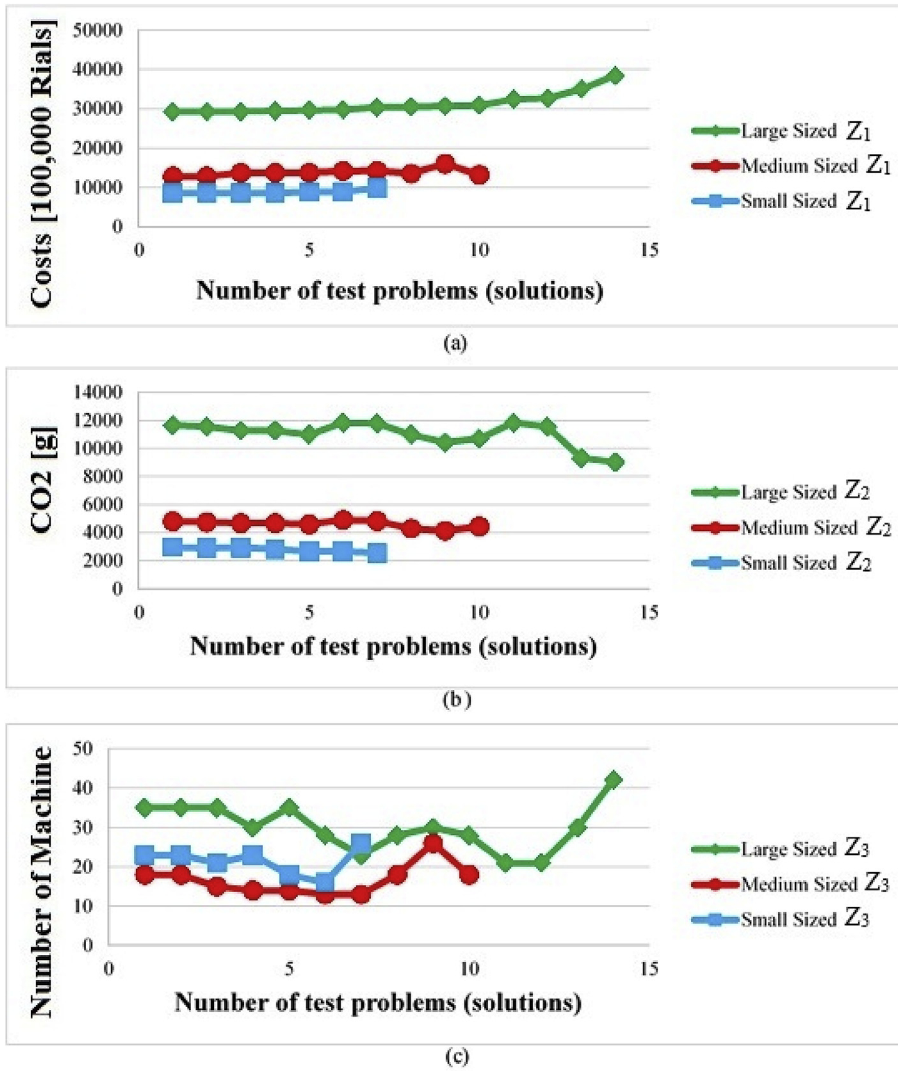


**Fig. 5.** Objective values for three size sample problems: (a) $Z_1$, (b) $Z_2$, and (c) $Z_3$.

**Table 11**
Changes in demand value for medium-size test problem in sensitivity analysis.

| Demand | Product 1 | Product 2 | Product 3 |
|---|---|---|---|
| Customer 1 | 33.36 | 26 | 29.3 |
| Customer 2 | 22.93 | 26.96 | 20.57 |
| Customer 3 | 23 | 25.5 | 33.263 |
| Demand of disposal | 11 | 9.6 | 9.41 |

used in the production lines) would initially decrease the CO2 emissions, albeit the $CO_2$ would increase as demand increases.

There are several suggestions for future improvements and research. First, the current model is a deterministic model, which may not reflect reality accurately Therefore, future studies can include uncertainty in the quality of return of the used products from customers, quality of the recovered products, demands, and in

**Table 12**
Change in Pareto values for medium-size test problem with changes in demand.

| Solution | Values of $Z_1$ [100,000 Rials] | Values of $Z_2$ [g] | Values of $Z_3$ [No. of machines] |
|---|---|---|---|
| 1 | 14067.75 | 5335.81 | 18 |
| 2 | 14110.91 | 5257.09 | 18 |
| 3 | 15174.56 | 5268.98 | 15 |
| 4 | 15178.33 | 5263.94 | 14 |
| 5 | 15181.00 | 5257.00 | 14 |
| 6 | 15682.59 | 5422.91 | 13 |
| 7 | 15758.8 | 5340.00 | 13 |
| 8 | 14967.43 | 7559.00 | 18 |
| 9 | 16815.57 | 4593.82 | 26 |
| 10 | 14172.14 | 5174.18 | 18 |

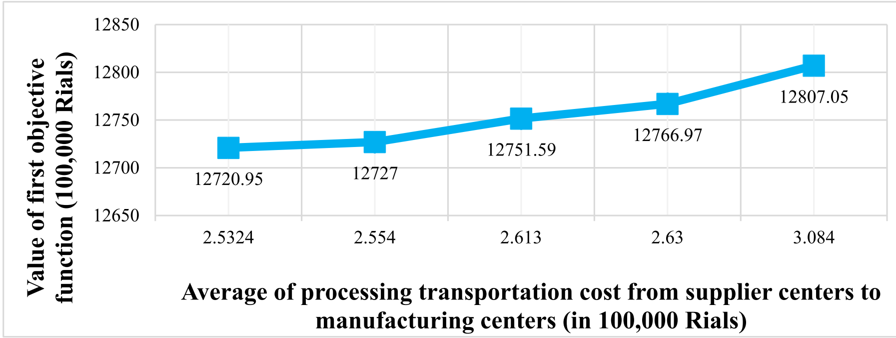


**Fig. 6.** Results of sensitivity analysis based on processing and transportation cost changes.

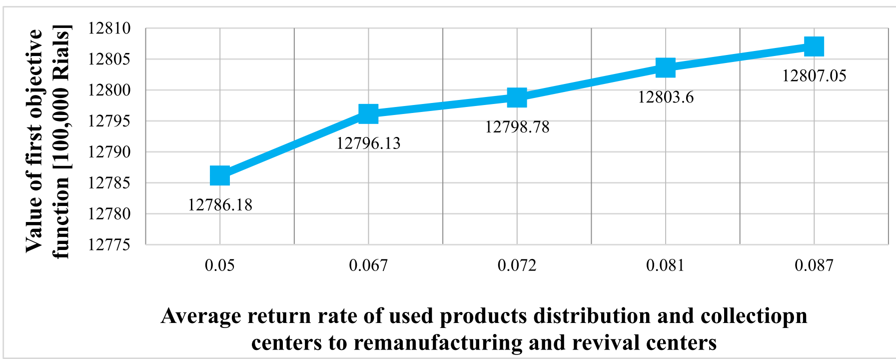


**Fig. 7.** Results of sensitivity analysis based on the rate of return of used products.

the amount of returns of the used products from the customers. Second, three objective functions have been considered so far: Costs, $CO_2$ emission, and the number of machines in the production line. Other objective functions can also be introduced at a later stage, such as social responsibility, and community welfare, so as to develop the model on the sustainability aspects. Third, the problem described in this paper is scalable to include multiple levels and nodes such as refurbishing and repairing centers. Lastly, while an exact solution method, the epsilon-constraint method, is used in this paper, there are many other exact methods and evolutionary algorithms for solving such multi-objective models.

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