SUSTAINABLE CLOSED-LOOP SUPPLY CHAIN NETWORK OPTIMIZATION FOR CONSTRUCTION MACHINERY RECOVERING

ABDOLHOSSEIN SADRNIA*
Assistant professor of department of Industrial Engineering
Quchan University of Technology, P.O. Box: 94771-67335, Quchan, Iran

AMIRREZA PAYANDEH SANI AND NAMJE ROGHANI LANGARUDI
Islamic Azad University of Semnan branch
Amirkabir University of Technology-Tehran Polytechnic, Iran
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Abstract. With regard to environmental pressures and economic benefits, some original construction equipment manufacturers, have focused on collecting and recovering construction machinery at the end of their life. The present study aimed to focus on Sustainable closed-loop supply chain network optimization for construction machinery recovering. To this purpose, different recovery options such as remanufacturing, recycling and reusing were implemented. A mixed integer linear programming model (MILP) including three objective functions was proposed in this regard. Based on the model, all three dimensions of sustainability including economic, environmental, and social dimensions were considered and could successfully determine the optimal values of the flow of used products, remanufactured products, recycled parts, re-usable parts. In order to demonstrate the applicability of the proposed model, a numerical example was used with the help of GAMS software to obtain the supply chain structure with the lowest cost and reduce the pollution caused by CO₂. Finally, the model could maximize fixed and variable job opportunities.

1. Introduction. Increasing urban populations, changing human lifestyles, rising welfare levels and living standards in urban communities have led to sustainable development in human society as a serious concern in recent years. In this regard, the government laws or regulations and the pressures of environmental librarians have increased, and the product recycling benefits have pushed companies to establish sustainable supply chain networks. So that, considering the sustainability of a supply chain design (or redesign) for a company is a strategic choice (Chopra and Meindl, 2007). Sustainability has become a key issue in supply chain management during recent years. Although there are different concepts of sustainability, there is a major concept called “triple bottom line approach of sustainability”, including economic, environmental and social aspects. In addition, an increase in customers’ awareness of sustainability problem in supply chain should be highlighted as a priority. During the recent years, researchers have attempted to integrate scientific
methods with supply chain management through sustainability. In advanced technology and manufacturing, conventional supply chain management is related to both economic perspectives and environmental and social effect of sustainability. Sustainability attributes refer to costs, environmental aspects such as GHG emissions and waste, as well as social aspects such as create job opportunities, support for local suppliers, and job satisfaction.

The optimal closed loop supply chain network design has always been regarded as an interesting area for research. Traditionally, the optimization models used in designing a strategic network aimed to focus on the economic aspect of supply chains (Goetschalcks and Fleischmann, 2008). Further, the economic aspect refers to the cost or the profit in net present value (Pistikopoulos and Hugo, 2005). Furthermore, the optimization targets were formulated as a single objective function in the form of the total cost. The combination of financial and other operational performance indicators in a multi-objective formulation has been widely implemented in supply chain studies such as cost, customer service, and the use of capacity (Altiparmak et al., 2006), cost, delivery time, and quality (Che and Chiang, 2010), profit and supplier defects (Franca et al., 2010), cost and lead time (Cardona-Valdes et al., 2011; Moncayo-Martinez and Zhang, 2011), cost and profit (Roy et al., 2017), cost, lead time, and lost sales (Liu and Papageorgiou, 2013), and cost and facility location (Das, Roy et al. 2019). Besides the sustainable aspect in supply chain, some of novel researches have been considered parameters' uncertainty for planning supply chain (Roy et al., 2017). Roy and Midya (2019) discussed the multi-objective fixed-charge solid transportation problem with product blending in intuitionistic fuzzy environment in a paper.

However, people's awareness about environmental issues has raised during recent years, for this reason few approaches have been reported on integrating financial and environmental issues in supply chain design (e.g., Wang et al., 2011; Jamshidi et al., 2012; Puzo et al., 2012; Sabio et al., 2012; Giarola et al., 2011). In another study, Guillen-Gosalbez and Grossmann (2009) presented a model for designing supply chain network including structural and planning decisions to determine the supply chain configuration, which can maximize the net present value and minimize the environmental impact. Cruz and Wakolbinger (2008) analyzed the effects of social responsibility on the supply chain and the behavior of manufacturers, retailers and customers under different conditions. Sustainability Reporting Guidelines (GRI, 2013) help organizations to measure their performance in three dimensions of sustainability, which is usually used by companies to monitor their evolution on sustainability issues (Roca and Searcy, 2012). Pishvaee et al. (2012) proposed a multi-objective model for designing sustainable supply chain networks with regard to economic, environmental and social factors. They provided a single-period, multi-level and multi-product model with a transportation mode. This model does not take into account some of the important environmental targets (such as gas emissions during the supply chain, warehousing waste). In another study, Mathivanthan et al. (2018) investigated the sustainable supply chain in Indian automotive industry by focusing on the consumers’ pressure, and government regulations for a competitive edge which had forced the automotive industry in order to consider economic, environmental and social dimensions. Chaabane et al. (2012) proposed a multi-mixed integer linear programming (MMILP) model based on the Life-Cycle Assessment (LCA) approach for designing supply chain. In their model, the economic and environmental dimensions were considered, but social dimension was not
included in this work. Furthermore, Mota et al. (2015) suggested a comprehensive multi-objective mathematical programming model in order to minimize cost and environmental impact, and maximize social benefit. This study did not pay attention to the environmental impact of warehousing and only one social advantage, namely the creation of jobs in less developed regions, was considered. Das et al. (2019) analyzed multi-objective model under reflection of carbon tax, cap and trade policy. Consideration of variable carbon emission cost due to variable potential sites. Regarding sustainable supply chains, Eskandar Pour et al. (2015) reviewed research gaps by reviewing 87 articles on supply chain design by considering environmental and social criteria in their modeling, and providing a comprehensive analysis of these issues. In addition, Zhang et al. (2018) published an article on sustainable supply chain management and corporate social responsibility by suggesting a hierarchical structure of sustainable supply chain management. Carter and Jennings (2002) proposed an important step in integrating the concepts of Corporate Social Responsibility (CSR) in the field of supply chain management (SCM) as the main work in this area. Roy et al. (2017) formulated the mathematical model of two-stage multi-objective transportation problem and designed the feasibility space based on the selection of goal values and they tried to consider the uncertainty in real-life situations.

On the other hand, in order to increase the utilization of resources and reduce environmental pollution, many companies use the product remanufacturing strategy. Some studies reported that companies can save 40%-65% in costs, which is achieved through using product remanufacturing strategies, which saves raw materials for producing new components and prevents from wasting the resources (Kerr & Ryan 2001). In the construction machinery industry, reconstruction strategy is also very important. Construction machinery at the end-of-life, if not properly managed, may lead to hazardous waste and environmental pollution. Fortunately, a large number of firms have allocated enough time for collecting and recovering the construction machinery due to the economic benefits, environmental regulations and customer awareness. In fact, firms must take responsibility for their products, in order to achieve the target of sustainable development. The problems of Construction Machinery recovering are more intricate than the other fields such as recovering paper, digital camera or phones. For this reason, a sustainable supply chain network design is necessary to collect and recovery construction machinery at the end of their life. A well-designed logistics network saves the cost in the process of collecting and recovering the arising flow of used products and it can be beneficial for the environment (Garg et al., 2015). Indeed, reverse logistics system planning is important because it increases the take-back rate. On the other, optimizing the forward and reverse network simultaneously, instead of optimizing the reverse network alone, can result in creating a significant cost benefit if there is a considerable difference between forward and reverse channels (Fleischmann et al., 2001).

Since the end-of-life home appliances have been given special attention, Taiwan has announced that scrap home appliances and Computers should be taken back by manufacturers and their suppliers for recycling. In this regard, Shih (2001) designed a reverse logistics system for recycling electrical appliances and computers in Taiwan. Zhao et al. (2011) referred to the vehicle recycling system in China and Japan. How to deal with the problem of end-of-life vehicles and environmental pollution caused by them is an issue that the automobile industry faces in all countries. This paper compared the present situation of scrap automobiles between
SADRnia, PayandeH Sani and ROghani Langarudi

Japan and China and tried to find an appropriate way for China to deal with the problem of scrap automobiles.

On the other hand, in the construction machinery industry, Caterpillar changed its construction strategy and sale of new construction equipment to lease and restructure (Gutowski et al., 2001) and expanded its market to contractors. In another study, Yi et al. (2016) designed a closed loop supply chain network for the remanufacturing of construction machinery. They developed a mixed integer linear programming model and implemented an improved hybrid genetic algorithm. Finally, in order to demonstrate the applicability of the model, they evaluated a firm in Japan. However, it considered economy side of sustainability but in this research, the environmental pollution caused by the remanufacturing and social dimension is not taken into account.

Regarding all the above-mentioned studies, no study, to the best of our knowledge, has investigated the Sustainable closed-loop supply chain network optimization for Construction Machinery recovering. Furthermore, considering the Sustainable supply chain for construction machinery recovering, with the present network structure and topology is regarded as another innovation in the present study. In the present study, a mixed integer linear programming was presented for configuring the supply chain network. The proposed model aims to maximize the recovery rate of construction machinery through remanufacturing, recycling and reusing the components in the end-of-life cycle. In fact, minimizing the total supply chain networks cost as an economical aspect, minimizing CO\textsubscript{2} emission throughout the network as an environmental issue, and maximizing the job opportunity in the supply chain are regarded as three main objective functions. In this study, the integrated network including reverse and forward logistics network was proposed due to the complexity of collecting and remanufacturing, recycling and reusing processes of construction machinery, as well as the mutual effective of forward and reverse logistic together.

The remainder of the paper is as follows. Section 2 describes the statement of the problem. Section 3 presents mixed-integer linear programming model for Construction Machinery recovering. Section 4 focuses on numerical examples and model solving. Sensitivity analysis is performed on some model parameters in Section 5. Finally, the concluding remarks are pinpointed in Section 6.

2. Statement of the problem. The process of recovery of construction machinery is generally complicated. Because they need to be disassembled at first. Then, the separated components undergo regeneration, sorting, recovery, and re-assembly processes. Therefore, the combined assembly / disassembly facility should be added to the supply chain network.

In the present study, Sustainable closed-loop supply chain network was designed for construction machinery recovering at the end of its life. This network includes consumer zones and suppliers, along with some centers such as collection and distribution, assembly and disassembly, disposal, remanufacturing, reusing, and recycling. Since the construction machinery is divided into parts at the end of its life, these parts can be recyclable or reused, in addition to their remanufacturing features. Hence, this facility is considered in the present study. The flows of products and parts between various facilities are regarded as the decision variables in the model. As illustrated in Figure 1, the supply chain is designed to be used for the products in consumer zones which are collected and transferred to the combined collection / distribution facility.
Then, they are sent to assembly / disassembly centers and they are mainly isolated and inspected. Finally, their quality status determines their next destination. In addition, highly damaged areas that have no repairable defects are sent to disposal sites. In the next step, those parts need remanufacturing are transferred to the remanufacture center. Some of the components are transferred to the recycling center while some prepared for reusing are sent to the reusing center. Those used parts which are reusable from reuse center are entered into the consumer zones. Then, the recycled parts are sent the recycling center to the supplier’s center. On the other hand, the suppliers of new parts select an alternative for severely damaged parts, and the disassembled components are delivered to assembly / disassembly centers. Finally, the products are reassembled on each other and re-sold through distribution channels (collection / distribution center).

In the present study, a mixed integer linear programming model was considered, along with three-objective functions for the network. The first objective function reduces network costs (economic dimension as the first dimension of a sustainable supply chain). The second objective function reduces the pollution caused by CO₂ released through transportation between the various facilities and the pollution caused by product remanufacturing (environmental dimension as the second dimension of the sustainable supply chain). The third objective function increases fixed and variable job opportunities in the supply chain (social dimension as the third dimension of the sustainable supply chain).

3. **Mathematical model.** Before creating the math model, some assumptions for using the proposed model are as follows:

   - Customer demand for the remanufactured product must be met.
   - There is no flow between facilities of the same level.
   - Remanufactured products and new products are unrecognizable for the customer (Ferrer and Swaminathan, 2006).
   - Recycled parts and new parts are indistinguishable.
   - Vehicles used for carrying products have limited capacity.

In this section, a multi-objective mixed-integer linear programming model is developed to configure the Sustainable closed-loop supply chain network. In this regard, the sets, parameters, and decision variables are as follows:
3.1. Sets.

\[ C = \{1, 2, \ldots, c\} \] Set of consumer zone
\[ D = \{1, 2, \ldots, d\} \] Set of collection /distribution centers
\[ A = \{1, 2, \ldots, a\} \] Set of potential Assembly / Disassembly centers locations
\[ RM = \{1, 2, \ldots, rm\} \] Set of potential remanufacture centers locations
\[ RC = \{1, 2, \ldots, rc\} \] Set of potential recycling centers locations
\[ RU = \{1, 2, \ldots, ru\} \] Set of potential reusing centers locations
\[ L = \{1, 2, \ldots, l\} \] Set of disposal centers
\[ S = \{1, 2, \ldots, s\} \] Set of suppliers
\[ TC = \{1, 2, \ldots, tc\} \] Transportation options from consumers
\[ TD = \{1, 2, \ldots, td\} \] Transportation options from collection /distribution centers
\[ TA = \{1, 2, \ldots, ta\} \] Transportation options from Assembly / Disassembly centers
\[ TS = \{1, 2, \ldots, ts\} \] Transportation options from suppliers
\[ M = \{1, 2, \ldots, m\} \] Set of products
\[ P = \{1, 2, \ldots, p\} \] Set of components

3.2. Parameters.

\[ CTR_{tc}^{m} c d \] The transportation cost of used products per km between consumer zone and collection /distribution centers with transportation option tc.
\[ CTR_{td}^{m} d a \] The transportation cost of used products per km between collection /distribution centers and Assembly / Disassembly centers with transportation option td.
\[ CTR_{ta}^{p} a rm \] The transportation cost of used parts per km between Assembly/ Disassembly centers and remanufacturing centers with transportation option ta.
\[ CTR_{ta}^{p} a rc \] The transportation cost of used parts per km between Assembly/ Disassembly centers and recycling centers with transportation option ta.
\[ CTR_{ta}^{p} a ru \] The transportation cost of reusable parts per km between Assembly/ Disassembly centers and reusing centers with transportation option ta.
\[ CTR_{ta}^{p} a l \] The transportation cost of disposal parts per km between Assembly/ Disassembly centers and disposal centers with transportation option ta.
\[ CTR_{ts}^{p} s a \] The transportation cost of new parts per km between suppliers and Assembly / Disassembly centers with transportation option ts.
\[ CTR_{tc}^{p} ru c \] The transportation cost of reusable parts per km between reusing centers and consumer zone with transportation option tc.
\[ CTR_{ts}^{p} rc s \] The transportation cost of recycled parts per km between recycle centers and suppliers with transportation option ts.
$CTR_{ta \_rm}$: The transportation cost of remanufactured parts per km between remanufacturing centers and Assembly/Disassembly centers with transportation option $ta$.

$CTR_{ta \_ad}$: The transportation cost of remanufactured products per km between Assembly/Disassembly centers and collection/distribution centers with transportation option $ta$.

$CTR_{td \_dc}$: The transportation cost of remanufactured products per km between collection/distribution centers and consumer zone with transportation option $td$.

$\text{dis}_{c \_d}$: Distance from $c$ to $d$

$\text{dis}_{d \_a}$: Distance from $d$ to $a$

$\text{dis}_{a \_l}$: Distance from $a$ to $l$

$\text{dis}_{a \_rm}$: Distance from $a$ to $rm$

$\text{dis}_{a \_rc}$: Distance from $a$ to $rc$

$\text{dis}_{a \_ru}$: Distance from $a$ to $ru$

$\text{dis}_{rc \_s}$: Distance from $rc$ to $s$

$\text{dis}_{s \_a}$: Distance from $s$ to $a$

$\text{CAP}_a$: Capacity of Assembly/Disassembly centers

$\text{CAP}_{rm}$: Capacity of remanufacturing centers for parts

$\text{CAP}_{rc}$: Capacity of recycling centers for parts

$\text{CAP}_{ru}$: Capacity of reusing centers for parts

$\text{cd}_m$: Unit dismantling cost for product $m$ in Assembly/Disassembly centers

$\text{ca}_m$: Unit assembling cost for product $m$ in Assembly/Disassembly centers

$\text{ci}_i$: Unit inspection cost for parts

$\text{crm}_p$: Unit remanufacturing costs for part $p$ in remanufacturing centers

$\text{crc}_p$: Unit recycling costs for part $p$ in recycling centers

$\text{cru}_p$: Unit preparing cost for reusing the parts in reusing center

$\text{cs}_p$: Unit supplying cost for the parts

$F_{fa}$: Fixed cost for opening Assembly/Disassembly centers

$F_{frm}$: Fixed cost for opening remanufacturing centers

$F_{frc}$: Fixed cost for opening recycling centers

$F_{fru}$: Fixed cost for opening reusing centers

$F_d$: Cost for expanding a distribution center to a combined collection/distribution facility

$\lambda_c$: Collection ratio in the consumer’s zone

$\hat{I}$: Badly-damaged ratio of the used part

$\hat{I}$: Remanufacturing ratio of the used part

$\hat{I}$: Recycling ratio of the used part

$\hat{I}_r$: Reusing ratio of the used part

$q_c$: Supply for the used product in the consumer’s zone

$DR_c$: Demand for the remanufactured product in the consumer’s zone

$V_p$: Unit volume of the part in product

$e_{rm}$: Rate of released CO$_2$ to remanufacture one unit of the product in remanufacturing centers
The amount of CO\textsubscript{2} released by transportation option tc to send a unit of the used product from the consumer’s zone to collection /distribution centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option td to send a unit of the used product from collection /distribution centers to Assembly / Disassembly centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the used part from Assembly / Disassembly centers to remanufacturing centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the used part from Assembly / Disassembly centers to recycling centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the used part from Assembly / Disassembly centers to reusing centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the disposal part from Assembly / Disassembly centers to disposal centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ts to send a unit of the new part from suppliers to Assembly / Disassembly centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option tc to send a unit of the reusable part from reusing centers to the consumer’s zone for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ts to send a unit of the recycled part from recycling centers to suppliers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the remanufactured part from remanufacturing centers to Assembly / Disassembly centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option ta to send a unit of the remanufactured product from Assembly / Disassembly centers to collection /distribution centers for a unit distance.

The amount of CO\textsubscript{2} released by transportation option td to send a unit of the remanufactured product from collection /distribution centers to the consumer’s zone for a unit distance.

Capacity of transportation option tc

Capacity of transportation option td

Capacity of transportation option ta

Capacity of transportation option ts

The number of the fixed job opportunities created by launching the Assembly / Disassembly centers

The number of the fixed job opportunities created by launching the remanufacturing centers

The number of the fixed job opportunities created by launching the recycling centers

The number of the fixed job opportunities created by launching the reusing centers

The number of the created variable job opportunities by working in Assembly / Disassembly centers
\( \mu_{\text{rm}} \), The number of the created variable job opportunities by working in remanufacturing centers

\( \mu_{\text{rc}} \), The number of the created variable job opportunities by working in recycling centers

\( \mu_{\text{ru}} \), The number of the created variable job opportunities by working in reusing centers

3.3. Decision variables.

\[
\begin{align*}
Q_{mc \text{ a } \text{ c } d}^m & \quad \text{Quantity of the used products } m \text{ from } C \text{ to } D \text{ with transportation option } tc \\
Q_{\text{d d } \text{ a } \text{ a}}^m & \quad \text{Quantity of the used products } m \text{ from } D \text{ to } A \text{ with transportation option } td \\
Q_{\text{a a } \text{ rm}}^p & \quad \text{Quantity of the used parts } p \text{ from } A \text{ to RM } \text{ with transportation option } ta \\
Q_{\text{a a } \text{ rc}}^p & \quad \text{Quantity of the used parts } p \text{ from } A \text{ to RC } \text{ with transportation option } ta \\
Q_{\text{a a } \text{ ru}}^p & \quad \text{Quantity of the reusable parts } p \text{ from } A \text{ to RU } \text{ with transportation option } ta \\
Q_{\text{a a } \text{ l}}^p & \quad \text{Quantity of the disposal parts } p \text{ from } A \text{ to } L \text{ with transportation option } ta \\
Q_{\text{s a } \text{ a } \text{ a}}^p & \quad \text{Quantity of the new parts } p \text{ from } S \text{ to } A \text{ with transportation option } ts \\
Q_{\text{c ru c}}^p & \quad \text{Quantity of the reusable parts } p \text{ from RU } \text{ to } C \text{ with transportation option } tc \\
Q_{\text{s rc s}}^p & \quad \text{Quantity of the recycled parts } p \text{ from RC } \text{ to } S \text{ with transportation option } ts \\
Q_{\text{a a } \text{ rm } \text{ a}}^p & \quad \text{Quantity of the remanufactured parts } p \text{ from RM } \text{ to } A \text{ with transportation option } ta \\
Q_{\text{a a } \text{ d}}^m & \quad \text{Quantity of the remanufactured products } m \text{ from } A \text{ to } D \text{ with transportation option } ta \\
Q_{\text{a d } \text{ c } \text{ d}}^m & \quad \text{Quantity of the remanufactured products } m \text{ from } D \text{ to } C \text{ with transportation option } td
\end{align*}
\]

3.4. Binary variables.

\[
\begin{align*}
X_a & \quad X_a = 1 \text{ if Assembly / Disassembly center is open. Otherwise, } X_a = 0 \\
Y_{\text{rm}} & \quad Y_{\text{rm}} = 1 \text{ if remanufacturing center is open. Otherwise, } Y_{\text{rm}} = 0 \\
Z_{\text{rc}} & \quad Z_{\text{rc}} = 1 \text{ if recycling center is open. Otherwise, } Z_{\text{rc}} = 0 \\
W_{\text{ru}} & \quad W_{\text{ru}} = 1 \text{ if reusing center is open. Otherwise, } W_{\text{ru}} = 0
\end{align*}
\]

3.5. Objective functions. In the present study, three objective functions are considered as follows:
3.5.1. **First objective function: Minimizing cost.** In this objective function, the phrases 1-5 indicate the fixed cost of established centers. The phrases 6-17 represent the cost of transportation between different facilities. Regarding phrases 18-24, they demonstrate the costs of each unit for disassembly, inspecting parts, remanufacturing the parts, recycling and reusing the parts, as well as the cost related to supplying new parts by the supplier, respectively.

\[
\min Z_1 = \sum_a F_a X_a + \sum_{rm} F_{rm} Y_{rm} + \sum_{rc} F_{rc} Z_{rc} + \sum_{ru} F_{ru} W_{ru} + \sum_d F_d \\
+ \sum_{m,tc,c,d} Q_{tc,c,d}^m \times \text{dis}_{c,d} \times \text{CTR}_{tc,c,d}^m + \sum_{m,td,a} Q_{td,a}^m \times \text{dis}_{a} \times \text{CTR}_{td,a}^m \\
\times \text{dis}_{a} \times \text{CTR}_{td,a}^p + \sum_{p,ta,rm} Q_{ta,rm}^p \times \text{dis}_{ta,rm} \times \text{CTR}_{ta,rm}^p \\
\times \text{dis}_{ta,rm} \times \text{CTR}_{ta,rm}^l + \sum_{p,ts,s,a} Q_{ts,s,a}^p \times \text{dis}_{ts,s,a} \times \text{CTR}_{ts,s,a}^p \\
\times \text{dis}_{ts,s,a} \times \text{CTR}_{ts,s,a}^l + \sum_{p,ta,rm} Q_{ta,rm}^p \times \text{dis}_{ta,rm} \times \text{CTR}_{ta,rm}^p \\
+ \sum_{m,tc,ru,c} Q_{tc,ru,c}^m \times \text{dis}_{tc,ru,c} \times \text{CTR}_{tc,ru,c}^m + \sum_{m,td,c} Q_{td,c}^m \times \text{dis}_{td,c} \times \text{CTR}_{td,c}^m \\
+ \sum_{m,td,a} Q_{td,a}^m \times \text{cd}_m + \sum_{m,td,a} Q_{td,a}^m \times \text{ci} \\
+ \sum_{m,td,a} Q_{td,a}^m \times \text{ca}_m + \sum_{p,ta,rm} Q_{ta,rm}^p \times \text{cr}_{mp} \\
+ \sum_{p,ta,ru} Q_{ta,ru}^p \times \text{cr}_{pu} + \sum_{p,ts,s,a} Q_{ts,s,a}^p \times \text{cs}_p
\]

3.5.2. **Second objective function: Minimizing pollution CO\(_2\).** In this objective function, the first expression indicates the amount of the pollution CO\(_2\) caused by the product remanufacturer. Other phrases represent the pollution CO\(_2\) released through the transportation between the various facilities. We multiply the number of vehicles moving between facilities in the distance that the vehicle travels. Finally, we multiply the above results by the amount of pollution emitted by a vehicle. To calculate the number of vehicles moving between facilities, we divide the number of
products that need to be moved between facilities by vehicle capacity.

\[
\begin{align*}
\min Z_2 &= \sum_{rm} c_{rm} \sum_{p,a,rm} Q_{ta a rm}^p + \sum_{tc} eCD^{tc} \sum_{m,c,d} \left( \frac{Q_{tc d c}^m}{H_{tc}} \right) d_{sc d} \\
&+ \sum_{td} eDA^{td} \sum_{m,d,a} \left( \frac{Q_{td d a}^m}{H_{td}} \right) d_{sd a} \\
&+ \sum_{ta} eARM^{ta} \sum_{p,a,rm} \left( \frac{Q_{ta a rm}^p}{H_{ta}} \right) d_{sa rm} \\
&+ \sum_{ta} eARC^{ta} \sum_{p,a,rc} \left( \frac{Q_{ta a rc}^p}{H_{ta}} \right) d_{sa rc} \\
&+ \sum_{ta} eARU^{ta} \sum_{p,a,ru} \left( \frac{Q_{ta a ru}^p}{H_{ta}} \right) d_{sa ru} \\
&+ \sum_{ta} eAL^{ta} \sum_{p,a,l} \left( \frac{Q_{ta a l}^p}{H_{ta}} \right) d_{sa l} \\
&+ \sum_{ts} eSA^{ts} \sum_{p,s,a} \left( \frac{Q_{ts s a}^p}{H_{ts}} \right) d_{sa s} \\
&+ \sum_{tc} eRUC^{tc} \sum_{p,r,u,c} \left( \frac{Q_{tc r u c}^p}{H_{tc}} \right) d_{sr u c} \\
&+ \sum_{ts} eRCS^{ts} \sum_{p,rc,s} \left( \frac{Q_{ts rc s}^p}{H_{ts}} \right) d_{sr c s} \\
&+ \sum_{ta} eRMA^{ta} \sum_{p,rm,a} \left( \frac{Q_{ta rm a}^p}{H_{ta}} \right) d_{sr rm a} \\
&+ \sum_{ta} eAD^{ta} \sum_{m,a,d} \left( \frac{Q_{ta a d}^m}{H_{ta}} \right) d_{sa d} \\
&+ \sum_{td} eDC^{td} \sum_{m,d,c} \left( \frac{Q_{td d c}^m}{H_{td}} \right) d_{sd c}
\end{align*}
\]

3.5.3. Third objective function: Increasing positive social effects (increasing the number of job opportunities in the supply chain). In the third objective function, the job opportunities created by the CLSCN network are maximized. In this objective function, the phrases 1-4 show the fixed job opportunities created by installing assembly / disassembly, remanufacturing, recycling, and reusing facilities. Finally, the phrases 5-8 represent the created variables for job opportunities, which are different based on the capacity of the facility at each level. Variable job opportunities in the supply chain are affected by two factors: the number of products transferred to the relevant center and the capacity of the center. Whenever the ratio (number of products transferred to the center) to (center capacity) increases, the number of job opportunities increases. For example, the closer the ratio \( \frac{Q_{ta rm a}^p}{CAP_{ta}} \) is to one, the higher the value of the objective function. As a result, job opportunities in the supply chain will increase.
\[
\max Z_3 = \sum_{a \in A} \varphi_a X_a + \sum_{rm \in RM} \varphi_{rm} Y_{rm} + \sum_{rc \in RC} \varphi_{rc} Z_{rc} + \sum_{ru \in RU} \varphi_{ru} W_{ru} \\
+ \sum_{m,td,d,a} \mu_a \times \frac{Q_{td}^m}{CAP_a} \times a + \sum_{p,ta,a,rm} \mu_{rm} \times \frac{Q_{ta}^p}{CAP_{rm}} \times a \\
+ \sum_{p,ta,a,rc} \mu_{rc} \times \frac{Q_{ta}^p}{CAP_{rc}} + \sum_{p,ta,a,ru} \mu_{ru} \times \frac{Q_{ta}^p}{CAP_{ru}} 
\]

3.6. Constraint.

\[
\sum_{m \in M} \sum_{tc \in TC} \sum_{d \in D} Q_{tc}^m c a = q_c \lambda_c \quad \forall c \quad (1)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} Q_{td}^m d c \geq DR_c \quad \forall c \quad (2)
\]

\[
\sum_{td \in TD \in C} Q_{td}^m d c = \sum_{a \in A} Q_{ta}^m a d \quad \forall m, d \quad (3)
\]

\[
\sum_{tc \in TC \in C} Q_{tm}^m c d = \sum_{td \in TD \in A} Q_{td}^m d a \quad \forall m, d \quad (4)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} V_p Q_{td}^m d a = \sum_{ta \in TA} \sum_{rm \in RM} Q_{ta}^p a \times rm + \sum_{ta \in TA} \sum_{rc \in RC} Q_{ta}^p a \times rc \\
+ \sum_{ta \in TA} \sum_{ru \in RU} Q_{ta}^p a \times ru + \sum_{ta \in TA} \sum_{l \in L} Q_{ta}^p a \times l \quad \forall p, a \quad (5)
\]

\[
\sum_{p \in P} \sum_{ta \in TA} \sum_{rm \in RM} Q_{ta}^p a \times rm + \sum_{p \in P} \sum_{ts \in TS} \sum_{s \in S} Q_{ts}^p a \times s = \sum_{m \in M} \sum_{ta \in TA} \sum_{d \in D} Q_{ta}^m a \times d \quad \forall a \quad (6)
\]

\[
Q_{ta}^p a \times rm = Q_{ta}^p a \times rm \quad (7)
\]

\[
\sum_{ta \in TA} Q_{ta}^p a \times rc = \sum_{ts \in TS} \sum_{s \in S} Q_{ts}^p a \times rc \quad \forall p, rc \quad (8)
\]

\[
\sum_{ta \in TA} Q_{ta}^p a \times ru = \sum_{tc \in TC \in C} Q_{tc}^p a \times c \quad \forall p, ru \quad (9)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} \alpha V_p \times Q_{td}^m d a = \sum_{ta \in TA} \sum_{l \in L} Q_{ta}^p a \times l \quad \forall p, a \quad (10)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} \beta V_p \times Q_{td}^m d a = \sum_{ta \in TA \times RM} Q_{ta}^p a \times rm \quad \forall p, a \quad (11)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} \gamma V_p \times Q_{td}^m d a = \sum_{ta \in TA \times RC} Q_{ta}^p a \times rc \quad \forall p, a \quad (12)
\]

\[
\sum_{m \in M} \sum_{td \in TD} \sum_{d \in D} \theta V_p \times Q_{td}^m d a = \sum_{ta \in TA \times RU} Q_{ta}^p a \times ru \quad \forall p, a \quad (13)
\]
\[
\sum_{m \in M} \sum_{td \in TD} Q_{td \in D} + \sum_{m \in M} \sum_{ta \in TA} \sum_{rm \in RM} Q_{ta \in TA} \leq X_a \text{CAP}_a \quad \forall a
\]

\[
\sum_{p \in P} \sum_{ta \in TA} \sum_{a \in A} Q_{ta \in TA} \leq Z_{rc} \text{CAP}_{rc} \quad \forall rc
\]

\[
\sum_{p \in P} \sum_{ta \in TA} \sum_{a \in A} Q_{ta \in TA} \leq W_{ru} \text{CAP}_{ru} \quad \forall ru
\]

\[
\sum_{a \in A} X_a \leq \varphi_a
\]

\[
\sum_{rm \in RM} Y_{rm} \leq \varphi_{rm}
\]

\[
\sum_{rc \in RC} Z_{rc} \leq \varphi_{rc}
\]

\[
\sum_{ru \in RU} W_{ru} \leq \varphi_{ru}
\]

\[
X_a, Y_{rm}, Z_{rc}, W_{ru} \in \{0, 1\}
\]

Constraint 1 ensures that the products collected from consumer zone return to collection / distribution centers. Based on the constraint 2, the demand for remanufactured Construction Machinery in customer zone is met by collection / distribution centers. Constraint 3 ensures that the input remanufactured Construction Machinery are equal to the output remanufactured Construction Machinery at the collection / distribution center. Regarding the constraint 4, the input used products are equal to the output used products at the collection / distribution center. Constraint 5 guarantees the balance between the used products and parts in the assembly / disassembly center. The balance between the remanufactured parts or components in the assembly / disassembly center is guaranteed in the constraint 6. Constraint 7 ensures that all parts which are transferred to the remanufacture center, as well as all of the remanufactured and returned to the assembly / disassembly center. Constraint 8 ensures that the parts which have been transferred to the recycle center for recycling all recycled and supplied to the supplier. According to the constraint 9, the parts transmitted to the reusing center, which are ready for reusing after preparation, and are similarly transported to the consumer’s zone are guaranteed. Constraint 10 indicates the destroyed percentage of the severely damaged products. Constraint 11 represents the remanufactured percentage of the used parts. The constraint 12, 13, 14, and 15 indicate the recycled percentage of the used parts, the transmitted percentage of reusable components to the reusing center, the sent products to assembly / disassembly centers which are prohibited over capacity, and the sent parts to the remanufacturing centers which are prevented over capacity, respectively. Finally, the constraint 16, 17, 18, and 19 are described as the sent parts.
to the recycling centers prohibited over capacity, the sent parts to reusing centers prevented over capacity, binary variables, and non-negative variables, respectively.

4. **Numerical example.** In this section, a numerical example is given to illustrate the applicability of the proposed model. To this aim, two consumer zones, two collection / distribution centers, two assembly / disassembly centers, two disposal centers, two remanufacturing centers, two recycling centers, two reusing centers, and two supplier centers were selected. In addition, two types of transportation option with different capacities were used to transport the products and parts between the facilities. In this example, the products and components are considered as two types. The values of each of the model parameters are shown in Table 1.

Further, GAMS software Mode 32 was used for calculating the results. Table 2 indicate the optimal values of Qs (the flow of various types of products and components between facilities) and the optimal value of all three objective functions. The results of GAMS software are shown in Table 3.

| parameter | value | parameter | value |
|-----------|-------|-----------|-------|
| $CTR_{tc, d}$ | floor(uniform(1,1500)) | $F_d$ | floor(uniform(1,8000000)) |
| $CTR_{td, a}$ | floor(uniform(1,1650)) | $q_c$ | floor(uniform(1,25)) |
| $CTR_{ta, rm}$ | floor(uniform(1,1867)) | $DR_c$ | floor(uniform(1,100)) |
| $CTR_{ta, rc}$ | floor(uniform(1,1900)) | $V_p$ | floor(uniform(1,10)) |
| $CTR_{ta, ru}$ | floor(uniform(1,1972)) | $e_{rm}$ | floor(uniform(1,10)) |
| $CTR_{ta, l}$ | floor(uniform(1,2000)) | $eCD_{tc}$ | floor(uniform(1,130)) |
| $CTR_{ta, s}$ | floor(uniform(1,3613)) | $eDA_{td}$ | floor(uniform(1,40)) |
| $CTR_{te, c}$ | floor(uniform(1,2890)) | $eARM_{ta}$ | floor(uniform(1,50)) |
| $CTR_{te, s}$ | floor(uniform(1,4561)) | $eARC_{ta}$ | floor(uniform(1,90)) |
| $CTR_{te, rm}$ | floor(uniform(1,3000)) | $eARU_{ta}$ | floor(uniform(1,80)) |
| $CTR_{te, d}$ | floor(uniform(1,3700)) | $eAL_{ta}$ | floor(uniform(1,100)) |
| $CTR_{td, d}$ | floor(uniform(1,9000)) | $eSA_{ta}$ | floor(uniform(1,70)) |
| $dis_{c, d}$ | floor(uniform(1,100)) | $eRUC_{tc}$ | floor(uniform(1,120)) |
| $dis_{d, a}$ | floor(uniform(1,150)) | $eRCS_{ts}$ | floor(uniform(1,150)) |
| $dis_{l, t}$ | floor(uniform(1,200)) | $eRMA_{ta}$ | floor(uniform(1,190)) |
| $dis_{ra, m}$ | floor(uniform(1,300)) | $eAD_{ta}$ | floor(uniform(1,160)) |
| $dis_{ra, s}$ | floor(uniform(1,450)) | $eDC_{td}$ | floor(uniform(1,170)) |
| $dis_{ru, a}$ | floor(uniform(1,700)) | $H_{tc}$ | floor(uniform(1,5)) |
| $dis_{rc, s}$ | floor(uniform(1,950)) | $H_{td}$ | floor(uniform(1,5)) |
| $dis_{ra, a}$ | floor(uniform(1,800)) | $H_{ta}$ | floor(uniform(1,5)) |
| $CAP_{a}$ | floor(uniform(120,150)) | $H_{ts}$ | floor(uniform(1,5)) |
| $CAP_{rm}$ | floor(uniform(10,50)) | $\varphi_a$ | floor(uniform(1,6000)) |
| $CAP_{rc}$ | floor(uniform(10,50)) | $\varphi_{rm}$ | floor(uniform(1,8500)) |
| $CAP_{rn}$ | floor(uniform(10,50)) | $\varphi_{rc}$ | floor(uniform(1,7000)) |
| $cd_{m}$ | floor(uniform(1,100)) | $\varphi_{ru}$ | floor(uniform(1,9500)) |
| $ca_{m}$ | floor(uniform(1,130)) | $\mu_a$ | floor(uniform(1,5000)) |
| $cl_{a}$ | floor(uniform(1,90)) | $\mu_{rm}$ | floor(uniform(1,7000)) |
| $crm_{p}$ | floor(uniform(1,170)) | $\mu_{rc}$ | floor(uniform(1,9000)) |
It is worth noting that the Lp-metrics (Compromise Programming) method was used to transform three objective functions into an objective function in the present study. Since the functions are in conflict, LP-metric method was implemented to solve the model and turn the three objective functions into one. As a result, the following equation was used as shown in Table 2.

$$\text{Minimize } lp - \text{metrics} = w_1 \times \left( \frac{Z_1 - Z^*_1}{Z^*_1} \right) + w_2 \times \left( \frac{Z_2 - Z^*_2}{Z^*_2} \right) + w_3 \times \left( \frac{Z^*_3 - Z_3}{Z^*_3} \right)$$

$$w_1 + w_2 + w_3 = 1$$

| The optimal value of the first objective | The optimal value of the second objective function | The optimal value of the third objective function |
|-----------------------------------------|--------------------------------------------------|-----------------------------------------------|
| 2.764708E+8                            | 6.2554E+9                                       | 47600.110                                     |

Table 3. The values obtained from the GAMS software for variables

| $Q^m_{tc \ c \ d}$ | Consumer Zones | Collection & Distribution | Product Type 1 |
|--------------------|----------------|---------------------------|----------------|
|                    | Centers        | Transportation option 1   | 3.245          |
|                    |                | Transportation option 2   | 0              |
|                    | 1 $\rightarrow$ 1 |                      | 13.311         |
|                    | 1 $\rightarrow$ 2 |                      | 0              |
|                    | 2 $\rightarrow$ 2 |                      | 1.023          |

|                       | Consumer Zones | Collection & Distribution | Product Type 2 |
|-----------------------|----------------|---------------------------|----------------|
|                       | Centers        | Transportation option 1   | 3.245          |
|                       |                | Transportation option 2   | 0              |
|                       | 1 $\rightarrow$ 1 |                      | 14.334         |
|                       | 2 $\rightarrow$ 2 |                      | 1.023          |

|                       | Consumer Zones | Collection & Distribution | Product Type 3 |
|-----------------------|----------------|---------------------------|----------------|
|                       | Centers        | Transportation option 1   | 3.245          |
|                       |                | Transportation option 2   | 0              |
|                       | 1 $\rightarrow$ 1 |                      | 1.023          |
|                       | 2 $\rightarrow$ 2 |                      | 0              |
| $Q_{td\, d\, a}$ | Collection & Distribution | Disassemble & Assemble | Product Type 1 | Transportation option 1 | Transportation option 2 |
|----------------|--------------------------|-----------------------|----------------|------------------------|------------------------|
| 2 $\rightarrow$ 1 | 0                        | 3.245                 | 0              | 13.311                 |
| 2 $\rightarrow$ 2 | 0                        | 13.311                |

| Collection & Distribution | Disassemble & Assemble | Product Type 2 | Transportation option 1 | Transportation option 2 |
|--------------------------|-----------------------|----------------|------------------------|------------------------|
| 2 $\rightarrow$ 1        | 0                     | 16.556         | 0                      | 0                      |
| 2 $\rightarrow$ 2        | 1.023                 | 16.556         |

| Collection & Distribution | Disassemble & Assemble | Product Type 3 | Transportation option 1 | Transportation option 2 |
|--------------------------|-----------------------|----------------|------------------------|------------------------|
| 2 $\rightarrow$ 1        | 12.02                 | 0              | 7.98                   |
| 2 $\rightarrow$ 2        | 0                     | 7.98           |

| $Q_{ta\, a\, rm}$ | Disassemble & Assemble | Remanufacture component Type 1 | Centers | Transportation option 1 |
|-------------------|------------------------|-------------------------------|---------|------------------------|
| 2 $\rightarrow$ 1 | 0                      | 8.897504E-4                  | 0.014   |
| 2 $\rightarrow$ 2 | 0                      | 8.897504E-4                  | 0.014   |

| Disassemble & Assemble | Remanufacture component Type 2 | Centers | Transportation option 1 |
|------------------------|-------------------------------|---------|------------------------|
| 2 $\rightarrow$ 1      | 0.006                          | 0.006   |
| 2 $\rightarrow$ 2      | 0.101                          |

| $Q_{ta\, a\, rc}$ | Disassemble & Assemble | Recycle component Type 1 | Centers | Transportation option 1 | Transportation option 2 |
|-------------------|------------------------|-------------------------|---------|------------------------|------------------------|
| 1 $\rightarrow$ 2 | 0                      | 12.429                  |
| 2 $\rightarrow$ 1 | 0.768                  | 12.429                  |

| Disassemble & Assemble | Recycle component Type 2 | Centers | Transportation option 1 | Transportation option 2 |
|------------------------|-------------------------|---------|------------------------|------------------------|
| 1 $\rightarrow$ 1    | 5.378                   | 0       |
| 1 $\rightarrow$ 2    | 0                       | 46.000  |
| 2 $\rightarrow$ 2    | 41.000                  | 0       |
| Component Type | Disassemble & Assemble | Re-use | Transportation option 1 | Transportation option 2 |
|----------------|------------------------|--------|--------------------------|--------------------------|
| Component Type 1 | Disassemble & Assemble | Re-use | Centers | 1 → 1 | 0 | 0.233 |
|                  |                        |        |         | 2 → 2 | 3.763 | 0 |
| Component Type 2 | Disassemble & Assemble | Re-use | Centers | 2 → 2 | 0.233 | 0 |
| Component Type 1 | Disassemble & Assemble | Disposal | Centers | 2 → 1 | 1.628 | 0 |
| Component Type 2 | Disassemble & Assemble | Disposal | Centers | 2 → 2 | 26.341 | 0 |
| Component Type 1 | Supplier | Disassemble & Assemble | Centers | 2 → 2 | 0.022 | 0 |
| Component Type 2 | Supplier | Disassemble & Assemble | Centers | 2 → 1 | 0.350 | 0 |
| Component Type 1 | Supplier | Disassemble & Assemble | Centers | 2 → 1 | 0.151 | 0 |
| Component Type 2 | Supplier | Disassemble & Assemble | Centers | 2 → 2 | 2.450 | 0 |
| Component Type 1 | Re-use | Consumer Zones | Centers | 2 → 2 | 4.272 | 54.621 |
| Component Type 1 | Supplier | Disassemble & Assemble | Centers | 2 → 2 | 4.277 | 54.708 |
| Component Type 1 | Supplier | Disassemble & Assemble | Centers | 2 → 2 | 4.272 | 54.621 |
| Re-use | Consumer Zones | component Type 2 |
|--------|----------------|------------------|
|        | Centers        | Transportation option 1 |
|        | 1 $\rightarrow$ 2 | 27.969 |

| Recycle | Supplier | component Type 1 |
|---------|----------|------------------|
|         | Centers  | Transportation option 1 |
|         | 1 $\rightarrow$ 1 | 0.768 |
|         | 1 $\rightarrow$ 2 | 12.429 |

| Recycle | Supplier | component Type 2 |
|---------|----------|------------------|
|         | Centers  | Transportation option 1 |
|         | 1 $\rightarrow$ 1 | 46.378 |
|         | 2 $\rightarrow$ 2 | 46.000 |

| Remanufacture | Disassemble & Assemble | component Type 1 |
|---------------|------------------------|------------------|
|               | Centers                | Transportation option 1 |
|               | 2 $\rightarrow$ 1     | 8.897504E-4       |
|               |                        | 0.014             |

| Remanufacture | Disassemble & Assemble | component Type 2 |
|---------------|------------------------|------------------|
|               | Centers                | Transportation option 1 |
|               | 2 $\rightarrow$ 1     | 0.006             |
|               |                        | 0.101             |

| Disassemble & Assemble | Collection & Distribution | Product Type 1 |
|------------------------|----------------------------|----------------|
|                        | Centers                    | Transportation option 1 |
|                        | 1 $\rightarrow$ 2          | 0                |
|                        | 2 $\rightarrow$ 1          | 4.278            |

| Disassemble & Assemble | Collection & Distribution | Product Type 2 |
|------------------------|----------------------------|----------------|
|                        | Centers                    | Transportation option 1 |
|                        | 1 $\rightarrow$ 2          | 0                |
|                        | 2 $\rightarrow$ 1          | 5.877            |

| $Q^p_{ls\, rc\, s}$ |
|---------------------|
| 1 $\rightarrow$ 2  | 27.969 |

| $Q^p_{la\, rm\, a}$ |
|---------------------|
| 2 $\rightarrow$ 1  | 8.897504E-4 |
| 2 $\rightarrow$ 1  | 0.014 |

| $Q^m_{la\, ad}$ |
|-----------------|
| 2 $\rightarrow$ 1 | 11.560 |
| 2 $\rightarrow$ 1 | 5.877 |
Based on the results of the GAMS software and the optimal values of each of the decision variables the optimal answer is obtained in different modes if we notice the variable $Q_{ta rc}^p$. For example, the optimal number of the used parts of type 1, which are transferred from the assembly / disassembly center 1 to the recycling center 2 with the transportation option 2, is 12.429, which is considered as 12. In addition, the optimal number of the used parts of type 2, which is sent from the assembly / disassembly center 2 to the recycling center 2 with the transportation option 1, is 41.

As another example, regarding the variable $Q_{td d c}^m$, the optimal number of the remanufactured products Type 1, which are transmitted from the collection / distribution center 1 to the consumer zones 2 with the transportation option 1, is 18. Such an analysis is also available for other variables.

5. Sensitivity analysis. Finally, the model behavior is examined by the changes in some of the main parameters of the model in order to evaluate the sensitivity of the model. We conduct a sensitivity analysis of the model with changes in the different three parameters; supply for the used product in the consumer’s zone, demand for the remanufactured product in the consumer’s zone and unit volume of the part (components) in product which are shown $q_c$, $DR_c$ and $V_p$ in order. The sensitivity analysis was done using GAMS.
5.1. **Sensitivity analysis on \( q_c \).** As indicated in Table 4, the supply for the used product in the consumer’s zone changed to evaluate the sensitivity of the objective function to \( q_c \) in this sensitivity analysis.

**Table 4. The amount of changes in the objective function for changes in \( q_c \).**

| Changes in \( q_c \) | Objective function |
|-----------------------|--------------------|
|                       | Numerical example 1| Numerical example 2| Numerical example 3| Numerical example 4 |
| 10                    | 1868132000        | 2619831            | 393784200         | 17291600            |
| 15                    | 1917029000        | 3027281            | 406228600         | 17744600            |
| 20                    | 1973978000        | 3497575            | 424883000         | 18274400            |
| 28                    | 2323844000        | 6807494            | 439768100         | 21675600            |
| 36                    | 3050361000        | 13929150           | 458673000         | 28832300            |
| 40                    | 3491321000        | 18206340           | 469234000         | 33176500            |
| 46                    | 3976855000        | 22915890           | 469987000         | 37959900            |

As illustrated in Figure 2, an \( q_c \) increases leads to an increase in the value of the objective function. In fact, increasing the supply of the used products in the consumer zone up to 28 results in increasing the amount of objective function with a lower slope. However, an increase in the value of the objective function is more slope if \( q_c \) is more than 28 units. In fact, as the number of used product in the consumer area (\( q_c \)) increases, more recyclables are sent to different centers and the operating costs resulting from remanufacturing, recycling and reuse, are increased and therefore total cost in logistic network would be increased.

**Figure 2. The change of the value of the objective function by changes in \( q_c \).**
5.2. **Sensitivity analysis on DRc.** As shown in Table 5, the demand was changed for the remanufactured product in the consumer’s zone to examine the sensitivity of the objective function to DRc.

Table 5. The amount of changes in the objective function for the changes in DRc.

| Changes in DRc | Objective function |
|----------------|-------------------|
| Numerical example 1 | Numerical example 2 | Numerical example 3 | Numerical example 4 |
| 10 | 440529700 | 21170450 | 347895400 | 183145000 |
| 50 | 1172853000 | 21968080 | 348972000 | 252260000 |
| 100 | 2042508000 | 22915890 | 359998700 | 331765000 |
| 150 | 2944460000 | 23905960 | 379543900 | 415302000 |
| 212 | 4289378000 | 24850110 | 391134100 | 494550000 |

Figure 3. The change in the value of the objective function by changes in DRc.

As illustrated in Figure 3, an increase in DRc leads to an increase in the objective function value. In other words, the value of the objective function increases when the value of DRc increases to 212. On the other words, as demand for remanufactured products (DRc) increases, the number of products transferred from the collection / distribution center to consumer areas increases, resulting in an increase in the objective function value.

5.3. **Sensitivity analysis on Vp.** In this sensitivity analysis, the unit volume of the part in product was modified to evaluate the sensitivity of the objective function to the Vp(Table 6).

As illustrated in Figure 4, an increase in the unit volume of the part in product to 19 units results in increasing the value of the objective function. In fact, in this
Table 6. The amount of changes in the objective function due to the changes in $V_p$

| Changes in $V_p$ | Objective function |
|------------------|--------------------|
|                  | Numerical example 1 | Numerical example 2 | Numerical example 3 |
| 5                | 4086738000          | 1017851700          | 2378543200          |
| 10               | 4289378000          | 1392022000          | 2598732700          |
| 15               | 5201699000          | 1898312000          | 2671340100          |
| 19               | 6184267000          | 2485011000          | 2812941300          |

Figure 4. The change in the value of the objective function by the changes in $V_p$.

sensitivity analysis the results show that as we increase the number of components in a product ($V_p$), more parts will need to be remanufactured, recycled, and each operation will incur costs to the network, thus total cost in the logistic network increased and the value of the target function also increases.

6. Conclusion. Today’s government organizations, environmental laws or legislations, and those who are concerned about the situation of the ecology have strongly urged companies to make their businesses more sustainable. The present study aimed to develop a mathematical model for the related companies to design CLSCN for recovering Construction Machinery by considering cost, CO$_2$ emission and job opportunity as the variables in the logistic network. To this aim, the location of the facility in the network was first identified and the optimal amount of the flow for the used products, remanufactured products, and recycled parts, re-usable parts were evaluated. Based on the results, designing a sustainable supply chain network for Construction Machinery recovering at the end of their life and utilizing various recovery options will manage waste and prevent their entry into nature. In addition, an increase in the return rate of the used products, demand for the remanufactured product in the consumer’s zone and the unit volume of the part in product; the value of the objective function increases. As a result, decision makers and supply chain
developers can consider all three dimensions of sustainability, and create a balance between gaining more profit and minimizing environmental pollution, which result in increasing the social impacts such as employment. In fact, implementing the results of the present research, designing a sustainable supply chain, and recovering the construction machinery include the following advantages:

First, the costs are decreased due to the savings resulting from recycling, remanufacturing and reusing construction machinery by designing a closed-loop supply chain network.

Second, the amount of pollution coming from the CO$_2$ released through transportation between facilities and that caused by remanufacturing the products and components is decreased.

Finally, the fixed job opportunities such as managerial jobs and some variables such as worker can be increasing by designing the Sustainable supply chain network due to the construction of remanufacturing, recycling, and reusing centers.

It is recommended that further research should be undertaken by considering some model parameters under uncertainty, maximizing some social benefits such as increased satisfaction of manufacturers of construction machinery and customers, considering the objective function that reduces the waste resulting from the disassembly of machinery, remanufacturing and recycling of components. As the number of centers increases, the mathematical model became more complex and it would be more time consuming by exact method and GAMS software. Since GAMS and Lingo software cannot solve the problem in complex problems, solving high-dimensional network problems can provide future research in this area by using heuristic and meta-heuristic algorithms.

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E-mail address: a.sadrnia@qiet.ac.ir
E-mail address: amirreza.payandeh@yahoo.com
E-mail address: najmeroghani@yahoo.com