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A Fuzzy Programming Based Approach to a Multi-Objective Multi-Echelon Green Closed-Loop Supply Chain Problem

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Abstract**:** *It has become a social and legal obligation to take into account environmental factors as well as economic factors when designing the supply chain network. Reducing the emission of harmful gases in supply chain operations, recycling and efficient use of resources must be taken into consideration for future generations. The supply chain created in this study, in addition to the above-mentioned features, includes supplier selection, warehouse and distribution center setup, transportation amounts between facilities, and transportation modes of products to be transported. This model, which is a multi-objective multi-echelon green closed-loop supply chain, is a mixed integer linear mathematical model and tries to maximize the joint satisfaction of the objectives with the help of a fuzzy approach using Zimmermann's minimum operator.*

Keywords**:** *Green supply chain, closed-loop supply chain, fuzzy multi-objective linear programming.*

1. Introduction

Supply Chain (SC) management increased its popularity in the 1980s and started to attract attention from the academic community. Since the number of studies is large and the sub-topics are also very diverse, it is very difficult to categorize the research area. While one-way SC (forward SC: from supplier to customer) studies have been carried out at first, the concept of the closed-loop SC has been focused on using the studies on the reverse SC. With the rise of environmental awareness, Green SC (GSC) studies have gained momentum. Especially since the beginning of the 2000s, studies in this field have been on a significant upward trend. In the field, there are specific studies for various sectors, as well as a large number of studies that deal with various aspects of the GSC process such as environmental, social, and economic, and there is a vast literature based on this. Therefore, it would be useful to start with the basic classifications on the subject.

B e a m o n [1] has focused on training multi-echelon SC models and has subclassed these in four models. These are deterministic analytical models, stochastic analytical models, economic models, and simulation models. M i n and Z h o u [2] have made a classification of SC problems into two separate classes according to integrated problem structures and model structures. In the classification made according to integrated problem structures; the literature has been examined under the titles of supplier selection-stock control, production-distribution, location selection-stock control, stock control-transport, and location selection-routing problems. According to the model structures, it has been examined under the titles of deterministic, stochastic, hybrid, and information technology processes. In [2] Min and Zhou, while deterministic models are classified based on the number of objectives, stochastic models are examined under the headings optimal control theory and dynamic programming. Also, hybrid models consist of stock-based and simulation-based models, and information technology process models are classified under the headings of the warehouse management system, enterprise resource planning, and geographic information systems.

There are some basic questions investigated in most of the studies on the SC. Some of these are: How many warehouses should be set up? How many distribution centers should be established? What should be the capacity of the facilities to be established? Where should the facilities be located? Which distribution center should serve which customer? Which factory should supply raw materials from which suppliers and what should be the purchase quantities? Which distribution center should serve which customers? Which mode of transport should be used when transporting products? Many studies have been conducted based on these and similar questions, and a vast literature has emerged. For a detailed literature analysis, Fahimnia, Sarkis and Davarzani [3] and Tseng et al. [4] can be reviewed.

In this study, a multi-objective multi-echelon green closed-loop SC model is proposed, which includes decisions about supplier selection, warehouse and distribution center setup, transportation amounts between facilities, and the transportation mode of the products to be transported. At this point, considering the fundamentals of our approach, we focus on studies in which SC problems are modeled through mathematical programming and the mode of transport is decided.

Cordeau et al. [5] have proposed a new formulation for the logistics network design problem. In the study, the model determines the location and capacity of the facility, as well as the supplier and the mode of transportation. In the decision process, two approaches are presented utilizing a simplex-based branch-bound algorithm, and the Benders decomposition approach. Wilhelm et al. [6] have conducted a strategic planning study and have offered a mixed-integer model that includes decisions such as location selection for the distribution center, technology, and capacity determination, supplier selection, and transportation mode planning. The goal is to maximize profit considering taxes. However, there is no environmental decision regarding CO_2 emissions in either of these two studies.

Pan, Ballot and Fontane [7] argue that logistics cooperation (consolidation of SCs) at the strategic level is an effective approach to reducing CO_2 emissions. They have compared road and rail transport and have shown that rail transport is an important factor in reducing CO_2 emissions. However, the economic dimension has not been taken into account in this study. Paksoy, Özceylan and Weber [8] have proposed a multi-objective model for GSC network optimization.

The model includes the CO_2 emissions caused by the mode of transportation, products produced from recyclable raw materials at different rates, some measures to encourage customers to use recyclable products, and penalties due to CO_2 emissions. However, in this model, the selection of the location and the CO_2 emission of the facilities are not included. In the study of Köfteci and Gerçek [9], the logit model, one of the stochastic selection models, has been used to model the transportation mode selection decisions of the users in freight transportation. It has also been determined that the main effective decision variables in the selection of transportation modes are the transportation cost and time and the transfer delay. Bouzembrak et al. [10] have conducted a study on the design of a GSC network. They propose a bi-objective model that assigns an upper limit for CO_2 emissions, decides on the setup of a warehouse and a distribution center, considers the transportation and setup costs, and the facility technologies, and includes different modes of transportation. However, the fact that the model is not closed-loop reduces the green level. Ozkok and Tiryaki [11] propose a fuzzy compensatory approach to the multi-objective linear programming model for the supplier selection problem in the multi-product SC structure. Laari et al. [12] have proposed an approach to determine the direct and indirect relationships between customer-oriented GSC applications and environmental and financial performance in the production process. Basiri and Heydari [13] have developed a two-stage analytical model on the GSC and have focused on a green product launch strategy. Pant et al. [14] have proposed a mixed-integer model for the closed-loop GSC problem, which considers supplier, manufacturer, distribution center, customer, collection, repair, disposal and recycling, destruction, and secondary market. Also, the solution of the model is presented with a branch-and-bound algorithm. Budiman and Rau [15] have proposed a mixed-integer model for the optimization of an integrated GSC network for both single and multi-period cases, which includes the concept of postponement and modular products and processes for mass customization. Guo, Yu and Gen [16] have proposed a mixed-integer nonlinear model in a closed-loop green system, taking into account online-offline sales modes and consumers' green preferences. Genetic algorithm and particle swarm optimization have been used in the solution phase. Rafigh et. al. [17] have developed a green supplier selection model considering green manufacturing, green transportation, and green procurement. They analyze the effects of the carbon tax and carbon cap on SC operations and have presented a global SC case study to demonstrate the model. Kara and Kocken [18] have presented a fuzzy approach to bring conflicting objectives – such as transportation cost, transportation time, transportation safety level, etc. – together as high as possible.

This study especially focuses on the effect of increasing environmental awareness in recent years on SC management. The proposed model helps to decide which supplier/suppliers to choose, where to set up warehouses and distribution centers, to minimize the total CO_2 emissions resulting from the production and transportation of the goods, and to minimize all setup and transportation costs. Besides all these benefits, the multi-objective multi-echelon green closed-loop SC model takes into account modes of transport and maximizes the percentage of importance of facilities. Thus, it prioritizes facilities that would be to the advantage of the company to establish, thereby giving optimal distribution by using Zimmermann's minimum operator within the context of the fuzzy approach. It is ensured that the optimal solution is to maximize the common satisfaction degree for all objectives. According to the given parameters, the model has determined from which supplier the raw material or semi-finished product will be purchased, the warehouse and distribution centers to be established, the amount of product to be transported between the facilities, the mode of transportation of the product to be transported, and customer demands.

The organization of the article is as follows: In the second section, the proposed model and the fuzzy approach to be used for the solution of this model are presented. In the third section, the applicability of the model is shown by presenting the data and calculation details of a hypothetical case study. And the conclusions are given in the final section.

2. A multi-objective multi-echelon green closed-loop supply chain problem

2.1. The assumptions of the model

All objective functions and constraints of the model are linear, and the locations of suppliers, production facilities, customer zones, and recycling centers are fixed and known in advance. The unit transportation costs of the products, which are calculated based on distances, and the amount of unit CO_2 emissions that will arise due to these transportations are certain. Quantity discounts and stocking status are not taken into account. The time parameter has not been taken into account, the model is created over a single period. The product is of a single type and consists of two components. Road transport is considered with three different fleet options. If desired, it can also be adapted to different modes of transport. The capacity of each facility and the amount of CO_2 emissions are determined.

2.2. Multi-objective mixed integer programming problem

The index sets, decision variables and parameters of the proposed model are as follows:

- Index sets:

s – Supplier index $(s = 1, 2, ..., S)$,

p – Plant (Factory) index $(p = 1, 2, ..., P)$,

w – Warehouse index $(w = 1, 2, ..., W)$,

d – Distribution center index $(d = 1, 2, ..., D)$,

cz – Customer Zone index (cz $= 1, 2, ...,$ CZ),

r – Recycling center index $(r = 1, 2, ..., R)$,

i – Component index $(i = 1, 2, ..., I)$,

h – Disposal center index $(h = 1, 2, ..., H)$,

j – Transportation mode index $(j = 1, 2, ..., J)$.

- Binary decision variables:

$$\text{yd}_d = \begin{cases} 1 & \text{if distribution center } d \text{ is setup,} \\ 0 & \text{otherwise,} \end{cases}$$

$$\text{xpw}_{pw} = \begin{cases} 1 & \text{if there is a link between } p \text{ and } w, \\ 0 & \text{otherwise,} \end{cases}$$

$$\text{xwd}_{wd} = \begin{cases} 1 & \text{if there is a link between } w \text{ and } d, \\ 0 & \text{otherwise,} \end{cases}$$

$$\text{xdcz}_{\text{dcz}} = \begin{cases} 1 & \text{if there is a link between } d \text{ and cz,} \\ 0 & \text{otherwise.} \end{cases}$$

- Continuous variables:

Qp_p: the production amount of factory *p*,

Qspji_{spji} – the amount of component *i* transported from *s* to *p* by the mode *j*,

Qpw_{pwj} – the amount of product transported from *p* to *w* by mode *j*,

Qwd_{wdj} – the amount of product transported from *w* to *d* by mode *j*,

Qdcz_{dczj} – the amount of product transported from *d* to cz by mode *j*,

Qczr_{czrj} – the amount of product transported from cz to *r* by mode *j*,

Qrpji_{rpji} – the amount of component *i* transported from *r* to *p* by the mode *j*,

Qrih_{rihj} – the amount of component *i* transported from *r* to *h* by the mode *j*.

- Parameters of the model:

SetupCostWH_w – the setup cost of *w*,

SetupCostDC_d – the setup cost of *d*,

Kp_p – the production capacity of *p*,

Kw_w – the capacity of *w*,

Kd_d – the capacity of *d*,

Dcz_{cz} – the demand quantity of cz,

ci_i – ratio coefficient of component *i*,

alt – the lower limit of the amount that can be transported at once,

$\text{ratingW}_w(\%)$ – the importance percentage of the region where *w* is located,

$\text{ratingD}_d(\%)$ – the importance percentage of the region where *d* is located,

Cp_p – the unit cost of production in *p*,

Cr_r – the unit recycling cost in *r*,

CPp_p – the unit CO_2 emission amount for production in factory *p*,

CWw_w – the unit CO_2 emission amount of warehouse *w*,

CDd_d – the unit CO_2 emission amount of distribution center *d*,

CRri_{ri} – the unit CO_2 emission amount for recycling component *i* in the center *r*,

ror – the percentage of product amount going from customers to recycling centers,

roc – the percentage of the amount recovered as a result of decomposition in the recycling center,

Cspij_{spij} – the unit transportation cost of component *i* transported from *s* to *p* by mode *j*,

Cpw_{pwj} – the unit transportation cost of product transported from *p* to *w* by mode *j*,

Cwd_{wdj} – the unit transportation cost of product transported from *w* to *d* by mode *j*,

Cdcz_{dczj} – the unit transportation cost of product transported from *d* to cz by mode *j*,

Cczr_{czrj} – the unit transportation cost of product transported from cz to *r* by mode *j*,

Crpi_{rpij} – the unit transportation cost of component *i* transported from *r* to *p* by mode *j*,

Crih_{rihj} – the unit transportation cost of component *i* transported from *r* to *h* by mode *j*,

$\text{CO}_2\text{spj}_{spj}$ – the unit CO_2 emission amount for transporting the product from *s* to *p* by mode *j*,

$\text{CO}_2\text{pwj}_{pwj}$ – the unit CO_2 emission amount for transporting the product from *p* to *w* by mode *j*,

$\text{CO}_2\text{wdj}_{wdj}$ – the unit CO_2 emission amount for transporting the product from *w* to *d* by mode *j*,

$\text{CO}_2\text{dczj}_{dczj}$ – the unit CO_2 emission amount for transporting the product from *d* to cz by mode *j*,

$\text{CO}_2\text{czrj}_{czrj}$ – the unit CO_2 emission amount for transporting the product from cz to *r* by mode *j*,

$\text{CO}_2\text{rpj}_{rpj}$ – the unit CO_2 emission amount for transporting the component from *r* to *p* by mode *j*,

$\text{CO}_2\text{rhj}_{rhj}$ – the unit CO_2 emission amount for transporting the component from *r* to *h* by mode *j*.

- Constraints:

(1) $$\text{Qwd}_{wdj} \geq \text{alt} \times \text{xwd}_{wdj} \qquad \forall w, \forall d, \forall j,$$

(2) $$\text{Qpw}_{pwj} \geq \text{alt} \times \text{xpw}_{pwj} \qquad \forall w, \forall p, \forall j,$$

(3) $$\text{Qdcz}_{dczj} \geq \text{alt} \times \text{xdcz}_{dczj} \qquad \forall d, \forall \text{cz}, \forall j,$$

(4) $$\sum_{w}^{W} y_w \geq 1,$$

(5) $$\sum_{d}^{D} y_d \geq 1,$$

(6) $$\mathrm{Qpw}_{pwj} \leq \mathrm{Kw}_w \mathrm{xpw}_{pwj} \qquad \forall p,\ \forall w,\ \forall j\ ,$$

(7) $$\mathrm{Qwd}_{wdj} \leq \mathrm{Kw}_w \mathrm{xwd}_{wdj} \qquad \forall w, \forall d, \forall j\ ,$$

(8) $$\mathrm{Qwd}_{wdj} \leq \mathrm{Kd}_d \mathrm{xwd}_{wdj} \qquad \forall w, \forall d, \forall j\ ,$$

(9) $$\mathrm{Qdcz}_{dczj} \leq \mathrm{Kd}_d \mathrm{xdcz}_{dczj} \qquad \forall d, \forall cz, \forall j\ ,$$

(10) $$\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qpw}_{pwj} \leq \mathrm{Kp}_p \qquad \forall p\ ,$$

(11) $$\sum_{p}^{P}\sum_{j}^{J} \mathrm{Qpw}_{pwj} \leq \mathrm{Kw}_w \mathrm{yw}_w \qquad \forall w,$$

(12) $$\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qwd}_{wdj} \leq \mathrm{Kw}_w \mathrm{yw}_w \qquad \forall w,$$

(13) $$\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qwd}_{wdj} \leq \mathrm{Kd}_d \mathrm{yd}_d \qquad \forall d\ ,$$

(14) $$\sum_{cz}^{CZ}\sum_{j}^{J} \mathrm{Qdcz}_{dczj} \leq \mathrm{Kd}_d \mathrm{yd}_d \qquad \forall d\ ,$$

(15) $$\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qdcz}_{dczj} = \mathrm{Dcz}_{\mathrm{cz}} \qquad \forall \mathrm{cz}\ ,$$

(16) $$\mathrm{Qp}_p = \sum_{w}^{W}\sum_{j}^{J} \mathrm{Qpw}_{pwj} \qquad \forall p\ ,$$

(17) $$\sum_{p}^{P}\sum_{j}^{J} \mathrm{Qpw}_{pwj} = \sum_{d}^{D}\sum_{j}^{J} \mathrm{Qwd}_{wdj} \qquad \forall w\ ,$$

(18) $$\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qwd}_{wdj} = \sum_{cz}^{CZ}\sum_{j}^{J} \mathrm{Qdcz}_{dczj} \qquad \forall d\ ,$$

(19) $$\mathrm{ror} \cdot \left(\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qdcz}_{dczj} \right) = \sum_{r}^{R}\sum_{j}^{J} \mathrm{Qczr}_{czrj} \qquad \forall \mathrm{cz}\ ,$$

(20) $$c_i \left(\sum_{\mathrm{cz}}^{\mathrm{CZ}}\sum_{j}^{J} \mathrm{Qczr}_{czrj} \cdot \mathrm{roc} \right) = \sum_{p}^{P}\sum_{j}^{J} \mathrm{Qrpji}_{rpji} \qquad \forall i, \forall r\ ,$$

(21) $$c_i \left(\sum_{\mathrm{cz}}^{\mathrm{CZ}}\sum_{j}^{J} \mathrm{Qczr}_{czrj} \left(1 - \mathrm{roc}\right) \right) = \sum_{h}^{H}\sum_{j}^{J} \mathrm{Qrih}_{rihj} \qquad \forall i, \forall r\ ,$$

(22) $$\sum_{s}^{S}\sum_{j}^{J} \mathrm{Qspji}_{spji} + \sum_{r}^{R}\sum_{j}^{J} \mathrm{Qrpji}_{rpji} = \mathrm{Qp}_p \cdot c_i \qquad \forall i, \forall p\ ,$$

(23) $$\mathrm{xpw}_{pwj} \leq \mathrm{yw}_w \qquad \forall p, \forall w, \forall j\ ,$$

(24) $$\mathrm{xwd}_{wdj} \leq \mathrm{yw}_w \qquad \forall w, \forall d, \forall j\ ,$$

(25) $$\mathrm{xwd}_{wdj} \le \mathrm{yd}_d \qquad \forall w, \forall d, \forall j,$$

(26) $$\mathrm{xdcz}_{dczj} \le yd_d \qquad \forall d, \forall \mathrm{cz}, \forall j,$$

(27) $$\sum_{p}^{P}\sum_{j}^{J} \mathrm{xpw}_{pwj} \ge \mathrm{yw}_w \qquad \forall w,$$

(28) $$\sum_{d}^{D}\sum_{j}^{J} \mathrm{xwd}_{wdj} \ge \mathrm{yw}_w \qquad \forall w,$$

(29) $$\sum_{w}^{W}\sum_{j}^{J} \mathrm{xwd}_{wdj} \ge \mathrm{yd}_d \qquad \forall d,$$

(30) $$\sum_{\mathrm{cz}}^{\mathrm{CZ}}\sum_{j}^{J} \mathrm{xdcz}_{dczj} \ge \mathrm{yd}_d \qquad \forall d.$$

Here, Equations (1), (2), and (3) ensure that the possible transports from factories to warehouses, from warehouses to distribution centers, and from distribution centers to customer zones do not fall below a certain value. Equations (4) and (5) ensure the establishment of at least one warehouse and one distribution center. Equations (6) (9) ensure that if there is no connection between the facilities, no transportation is made, and if there is a connection, the transportation to be made does not exceed the capacity of the facilities. Equation (10) is a production capacity constraint for the factory, while Equations (11)-(14) is a capacity constraint for incoming and outgoing products for warehouses and distribution centers. Equation (15) ensures that customer demands are met and Equation (16) ensures that the amount of production in the factories is equal to the amount that goes to the warehouses, thus preventing the stock in the factories. Equations (17) and (18) are equilibrium constraints for warehouse and distribution centers. Equations (19)-(21) are equilibrium constraints for the recycling process. Equation (22) provides product component balance. Equations (23)-(26) ensure that no connection is made to the corresponding facility when no warehouse or no distribution center is established. With Equations (27)-(30), is ensured that at least one connection is placed when any warehouse or distribution center is established.

- Variable type constraints:

(31) $$\mathrm{Qp}_p, \mathrm{Qspji}_{spji}, \mathrm{Qpw}_{pwj}, \mathrm{Qwd}_{wdj}, \mathrm{Qdcz}_{dczj}, \mathrm{Qczr}_{czrj}, \mathrm{Qrpji}_{rpji}, \mathrm{Qrih}_{rihj} \ge 0,$$

(32) $$\mathrm{yw}_w, \mathrm{yd}_d, \mathrm{xpw}_{pw}, \mathrm{xwd}_{wd}, \mathrm{xdcz}_{dcz} \in \{0,1\},$$

Equations (31) and (32) are defined for all $s, p, w, d, \mathrm{cz}, r, i, h, j$.

- Objective functions are three.

First objective function. It is the summation of transportation, production, recycling, and setup costs and will be minimized.

i. Transportation costs are

$$\sum_{s}^{S}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{Qspji}_{spji}\mathrm{Cspij}_{spij} + \sum_{p}^{P}\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qpw}_{pwj}\mathrm{Cpw}_{pwj} + \sum_{w}^{W}\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qwd}_{wdj}\mathrm{Cwd}_{wdj} +$$
$$+\sum_{d}^{D}\sum_{\mathrm{cz}}^{\mathrm{CZ}}\sum_{j}^{J} \mathrm{Qdcz}_{dczj}\mathrm{Cdcz}_{dczj} + \sum_{\mathrm{cz}}^{\mathrm{CZ}}\sum_{r}^{R}\sum_{j}^{J} \mathrm{Qczr}_{czrj}\mathrm{Cczr}_{czrj} + \sum_{r}^{R}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{Qrpji}_{rpji}\mathrm{Crpi}_{rpij} +$$
$$+\sum_{r}^{R}\sum_{i}^{I}\sum_{h}^{H}\sum_{j}^{J} \mathrm{Qrih}_{rihj}\mathrm{Crih}_{rihj}.$$

ii. Production cost is

$$\sum_{p}^{P} \mathrm{Qp}_p \mathrm{Cp}_p \ ,$$

iii. Recycling cost is

$$\sum_{cz}^{CZ}\sum_{r}^{R}\sum_{j}^{J} \mathrm{Qczr}_{czrj}\mathrm{Cr}_r \ .$$

iv. Setup costs are

$$\sum_{w}^{W} \mathrm{SetupCostWH}_w \, \mathrm{yw}_w + \sum_{d}^{D} \mathrm{SetupCostDC}_d \, \mathrm{yd}_d \ .$$

Thus, the first objective function of the model is:

(33)
$$\begin{aligned} Z_1 = &\sum_{s}^{S}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{Qspji}_{spji}\mathrm{Cspij}_{spij} + \sum_{p}^{P}\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qpw}_{pwj}\mathrm{Cpw}_{pwj} + \\ &+\sum_{w}^{W}\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qwd}_{wdj}\mathrm{Cwd}_{wdj} + \sum_{d}^{D}\sum_{cz}^{CZ}\sum_{j}^{J} \mathrm{Qdcz}_{dczj}\mathrm{Cdcz}_{dczj} + \sum_{cz}^{CZ}\sum_{r}^{R}\sum_{j}^{J} \mathrm{Qczr}_{czrj}\mathrm{Cczr}_{czrj} + \\ &+\sum_{r}^{R}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{Qrpji}_{rpji}\mathrm{Crpi}_{rpij} + \sum_{r}^{R}\sum_{i}^{I}\sum_{h}^{H}\sum_{j}^{J} \mathrm{Qrih}_{rihj}\mathrm{Crih}_{rihj} + \sum_{p}^{P} \mathrm{Qp}_p\mathrm{Cp}_p + \\ &+\sum_{cz}^{CZ}\sum_{r}^{R}\sum_{j}^{J} \mathrm{Qczr}_{czrj}\mathrm{Cr}_r + \sum_{w}^{W} \mathrm{SetupCostWH}_w \, \mathrm{yw}_w + \sum_{d}^{D} \mathrm{SetupCostDC}_d \, \mathrm{yd}_d . \end{aligned}$$

Second objective function. It consists of the total importance percentages of the warehouses and distribution centers that are to be established. The aim is to make the setup decision that will maximize the overall importance percentage:

(34)
$$Z_2 = \sum_{w}^{W} \mathrm{rating}W_w \sum_{p}^{P}\sum_{j}^{J} \mathrm{Qpw}_{pwj} + \sum_{d}^{D} \mathrm{rating}D_d \sum_{w}^{W}\sum_{j}^{J} \mathrm{Qwd}_{wdj} \ .$$

Third objective function. It is the sum of the amount of CO_2 emissions resulting from transportation, production, and other processes in the facilities. The aim is to minimize the total CO_2 emission amount. Thus, the third objective function is:

(35)
$$\begin{aligned} Z_3 = &\sum_{s}^{S}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{CO_2spj}_{spj}\mathrm{Qspji}_{spji} + \sum_{p}^{P}\sum_{w}^{W}\sum_{j}^{J} \mathrm{CO_2pwj}_{pwj}\mathrm{Qpw}_{pwj} + \\ &+\sum_{w}^{W}\sum_{d}^{D}\sum_{j}^{J} \mathrm{CO_2wdj}_{wdj}\mathrm{Qwd}_{wdj} + \sum_{d}^{D}\sum_{cz}^{CZ}\sum_{j}^{J} \mathrm{CO_2dczj}_{dczj}\mathrm{Qdcz}_{dczj} + \\ &+\sum_{cz}^{CZ}\sum_{r}^{R}\sum_{j}^{J} \mathrm{CO_2czrj}_{czrj}\mathrm{Qczr}_{czrj} + \sum_{r}^{R}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{CO_2rpij}_{rpij}\mathrm{Qrpji}_{rpji} + \\ &+\sum_{r}^{R}\sum_{i}^{I}\sum_{h}^{H}\sum_{j}^{J} \mathrm{CO_2rhj}_{rhj}\mathrm{Qrih}_{rihj} + \sum_{p}^{P}\sum_{w}^{W}\sum_{j}^{J} \mathrm{Qpw}_{pwj}\mathrm{Cp}_p + \\ &+\sum_{w}^{W}\sum_{d}^{D}\sum_{j}^{J} \mathrm{Qwd}_{wdj}\mathrm{CWw}_w + \sum_{d}^{D}\sum_{cz}^{CZ}\sum_{j}^{J} \mathrm{Qdcz}_{dczj}\mathrm{CDd}_d + \\ &+\sum_{r}^{R}\sum_{p}^{P}\sum_{j}^{J}\sum_{i}^{I} \mathrm{Qrpji}_{rpji}\mathrm{CRri}_{ri} + \sum_{r}^{R}\sum_{i}^{I}\sum_{h}^{H}\sum_{j}^{J} \mathrm{Qrih}_{rihj}\mathrm{CRri}_{ri}. \end{aligned}$$

While the first seven and the eighth terms of (35) represent the amount of CO_2 emissions from transportation and production, respectively, the final four terms of (35) represent the amount of CO_2 emissions resulting from operations in warehouses, distribution centers, and recycling centers. Thus, our multi-objective multi-echelon green closed-loop SC model can be given by (1)-(35). Let the feasible region of the model be denoted by S .

2.3. A fuzzy approach for the proposed model

For the solution of the proposed model given in (1)-(35), a fuzzy approach (Z i m m e r m a n n [19]), which is frequently used in the literature, will be presented. The first step in the approach is to construct the membership functions of all objectives for $k \in \{1, 2, \ldots, K\}$. For this purpose, each objective is minimized and maximized under the original constraints of the problem and, can be obtained as:

$$z_k^- = \min_{x \in S} z_k(x),\ z_k^+ = \max_{x \in S} z_k(x),\ k = 1, 2, \ldots, K. \tag{36}$$

Thus, the membership functions are:

$$\mu_k(z_k(x)) = \begin{cases} 0, & z_k(x) < z_k^-, \\ \dfrac{z_k(x) - z_k^-}{z_k^+ - z_k^-}, & z_k^- \le z_k(x) \le z_k^+, \\ 1, & z_k(x) > z_k^+, \end{cases} \tag{37}$$

$$\mu_k(z_k(x)) = \begin{cases} 1, & z_k(x) < z_k^-, \\ \dfrac{z_k^+ - z_k(x)}{z_k^+ - z_k^-}, & z_k^- \le z_k(x) \le z_k^+, \\ 0, & z_k(x) > z_k^+. \end{cases} \tag{38}$$

Here, (37) and (38) are the membership functions of the objectives to be maximized and minimized, respectively. The final version of our multi-objective model using Zimmermann's minimum operator can be given as follows:

$$\begin{gathered} \max \lambda, \\ \mu_k(z_k(x)) \ge \lambda,\ k = 1, 2, \ldots, K, \\ x \in S, \\ \lambda \in [0, 1]. \end{gathered} \tag{39}$$

The optimal λ^* value of this problem corresponds to the value at which the lowest satisfaction level of all the objectives is maximized and can be interpreted as the most basic level of satisfaction of the objectives in the original problem.

3. Implementation of the model

An X company, whose factory is located in Afyon, wants to go through an internal restructuring to provide better service to its customers in Turkey. Also considering the legal obligations, cost, and customer satisfaction, the company will make this restructuring in the form of transitioning to the GSC.

The company has three suppliers, one factory, nine customers, one recycling center, and one disposal center. Considering the customer demands, setup, and transportation costs, the company wants to establish at least one warehouse and at least one distribution center out of seven possible locations. Depending on the distance, offers have been received from three different suppliers for the transportation of goods regarding pricing and CO_2 emission amounts. The offers given are calculated by taking into consideration the transportation of at least 10000 units. While deciding to establish a warehouse and a distribution center, the CO_2 emissions of the facilities to be established, the amount of CO_2 emissions resulting from transportation, and the total transportation costs are to be minimized. It is also desired to maximize the predetermined importance percentages according to factors such like the location of each facility to be established with respect to the market and transportation centers, its superiority in production and marketing activities, the incentives given, labor supply, workforce type, and infrastructure services. The company's SC network is given in Fig. 1.

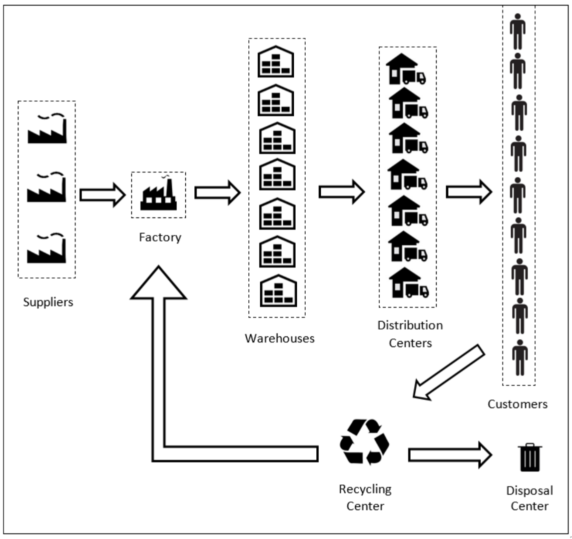

Fig. 1. The SC network of company X

The numerical data of the application can be summarized as:

$S=3$, $P=1$, $W=7$, $D=7$, $\mathrm{CZ}=9$, $R=1$, $I=2$, $H=1$, $J=3$, $\mathrm{Kp}_1=7{,}500{,}000$, $\mathrm{ror}=0.40$, $\mathrm{roc}=0.70$, $\mathrm{Cp}_1=3$, $\mathrm{Cr}_1=0.2$, $\mathrm{CPp}_1=0.5$, $\mathrm{alt}=10000$, $\mathrm{ci}_1=1$, $\mathrm{ci}_2=2$, $\mathrm{CRri}_{11}=2$, $\mathrm{CRri}_{12}=1$.

According to the order of indices, suppliers are in Kutahya, Usak, and Burdur; warehouses are in Canakkale, Mugla, Sakarya, Nigde, Tokat, Sanliurfa, and Erzurum; distribution centers are in Usak, Bursa, Bolu, Konya, Malatya, Trabzon, and Kars; customers are in Izmir, Istanbul, Antalya, Ankara, Samsun, Adana, Kahramanmaras, Ardahan and Van. And the recycling center is in Kirikkale and the disposal center is in Sinop. The numerical values of the other parameters have been retrieved by compiling from the websites of official institutions. Distances between facilities are taken from the website of the General Directorate of Highways of the Republic of Türkiye. Depending on the distance, the average unit transportation cost per km for the highway (D e m i r l i o g l u [20]) and the distance information are multiplied to obtain the transportation costs between the facilities. The average CO_2 emission amount per 1 km for the highway [20] has been obtained by multiplying the distance information by the CO_2 emission amounts resulting from the transportation. CO_2 emission data of the facilities is retrieved from the website of the Ministry of Energy and Natural Resources of the Republic of Turkey.

Our multi-objective linear model will be solved with the GAMS package program with the fuzzy approach presented in Section 2.3. The model is aimed to minimize the total cost and the total CO_2 emissions in the SC network and also to maximize the percentage of total importance of warehouses and distribution centers. Using (36), the upper and lower limit values of the objectives are obtained and given in Table 1.

Table 1. The individual optima of objectives

Objective	Maximum	Minimum
Objective 1	2.777567×10^8	3.605166×10^7
Objective 2	3.081500×10^8	1.953000×10^8
Objective 3	1.008636×10^9	1.712581×10^8

By the limit values in Table 1, the membership functions on the intervals $\left[Z_k^-, Z_k^+\right]$, $(k=1, 2, 3)$ are constructed as follows:

$$\mu_1\left(Z_1\left(x\right)\right)=\frac{277,756,700-Z_1}{277,756,700-36,051,660},$$

$$\mu_2\left(Z_2\left(x\right)\right)=\frac{Z_2-195,300,000}{308,150,000-195,300,000},$$

$$\mu_3\left(Z_3\left(x\right)\right)=\frac{1,008,636,000-Z_3}{1,008,636,000-171,258,100}.$$

Accordingly, the min operator model corresponding to (39) obtained for the application is as follows:

(40)
$$\max\lambda,$$
$$\text{s.t. } \frac{277,756,700-Z_1}{277,756,700-36,051,660}\geq\lambda,$$
$$\frac{Z_2-195,300,000}{308,150,000-195,300,000}\geq\lambda,$$
$$\frac{1,008,636,000-Z_3}{1,008,636,000-171,258,100}\geq\lambda,$$
$$x\in S,$$
$$0\leq\lambda\leq1.$$

The objective function values and the basic satisfaction level of the objectives obtained by solving the problem (35) are $Z_1 = 89,579,000$, $Z_2 = 277,900,000$ and $Z_3 = 339,090,000$. The SC network obtained by minimizing the first objective function is shown in Fig. 2, the SC network obtained by maximizing the second objective function – in Fig. 3, and the SC network obtained by minimizing the third objective function – in Fig. 4 and finally, Fig. 5 shows the optimal SC network in which common satisfactions are maximized by considering all three objective functions. In Fig. 2 – Fig. 5, different modes of transport are shown with arrows of different colors. Green, blue, and red arrows represent the first ($j = 1$), second $(j = 2)$, and third ($j = 3$) transport mode, respectively.

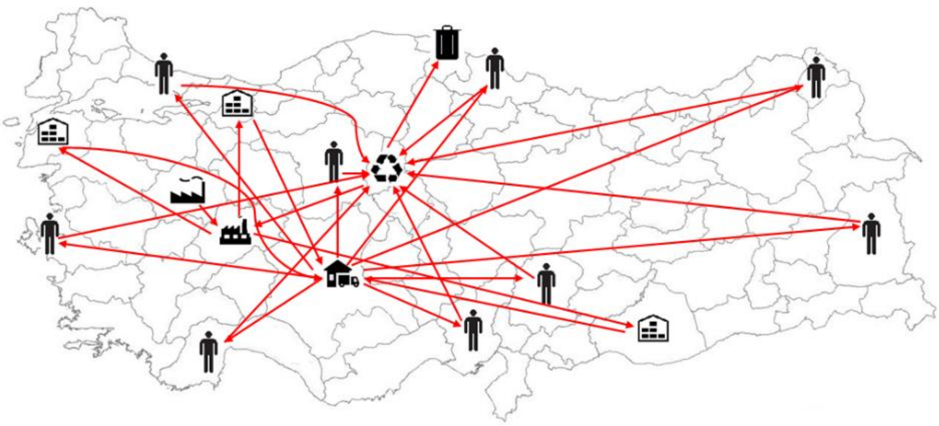

Fig. 2. Network corresponding to the individual minimization of the first objective

In the network in Fig. 2, the objective is to minimize transportation and plant installation costs. As a result, the model has established as few facilities as possible to reduce facility installation costs and reduced transportation costs as much as possible by establishing these facilities close to areas with high demand. three warehouses in Canakkale, Sakarya, and Sanliurfa and 1 distribution center in Konya are to be established. As can be seen, the warehouses in Canakkale and Sakarya and the distribution center in Konya are close to the western regions where demand is high. The transportation between these facilities is made with the third transport mode ($j = 3$). This mode of transportation is the least expensive compared to the others. The total cost is 36052000 currency units. However, since the first objective function does not take into account the emission, it is seen that the amount of CO_2 emission is quite high, such as 6358 million units.

In the network in Fig. 3, the goal is to make facility installation and transportation decisions that would maximize predetermined importance percentages. When the network is analyzed, it is seen that the decision to install 4 warehouses with the highest importance percentages and 2 distribution centers with the highest importance percentages has been taken. Warehouses are in Mugla, Nigde, Tokat, and Erzurum; distribution centers are established in Bolu and Konya. All modes of transport have been also utilized. The total cost is 91,930,000 currency units and the total CO_2 emission amount is 404,530,000 units.

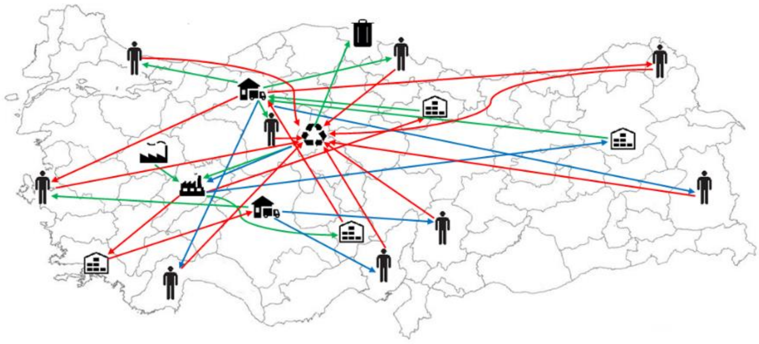

Fig. 3. Network corresponding to the individual maximization of the second objective

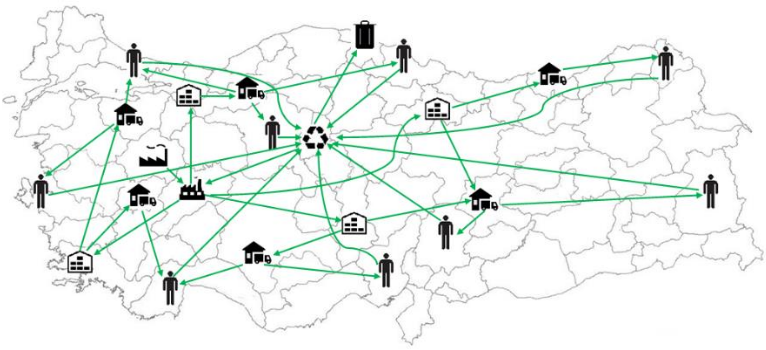

Fig. 4. Network corresponding to the individual minimization of the third objective

In the network in Fig. 4, the aim is to make plant installation and transportation decisions that would minimize CO_2 emissions. four warehouses are established in Mugla, Sakarya, Nigde, and Sanliurfa, and six distribution centers are established in Usak, Bursa, Bolu, Konya, Malatya, and Trabzon. When the resulting network is examined, it is seen that all transports are made with the transport mode with the lowest CO_2 emission. Since the network is created by considering only CO_2 emissions, the total cost is 139,100,000 currency units and the total importance percentage is 273,550,000. On the other hand, the total amount of CO_2 emission is 171,260,000 units.

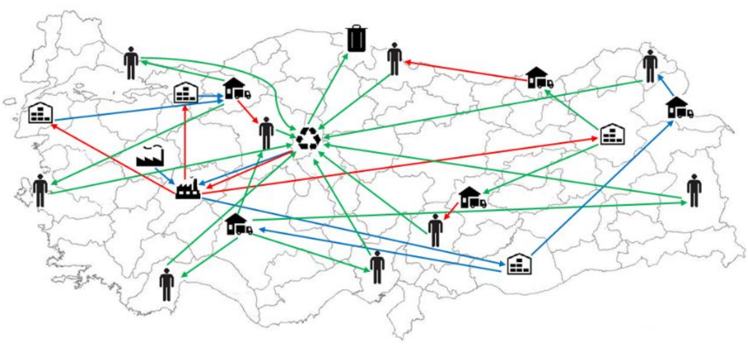

Fig. 5. Network corresponding to the maximization of the satisfaction of all objective functions

In Fig. 5, a network emerges that satisfies all three objectives as high as possible. In an optimal situation, it has been decided to establish four warehouses and five distribution centers. Warehouses are established in Canakkale, Sakarya, Sanliurfa, and Erzurum; distribution centers are established in Bolu, Konya, Malatya, Trabzon, and Kars. When the modes of transport are examined, it is seen that all three modes of transport are used at similar rates. When we look at the places where distribution centers are established, the fact that they are close to the customers they serve shows the consistency in the network. For example, the distribution center established in Bolu serves Izmir, Istanbul, and Ankara. The total cost is 89,579,000 currency units and the satisfaction level is 0.779. The overall significance percentage is 27,790,000 and is satisfied at the 0.732 level. The total amount of CO_2 emissions is 339,090,000 units and the satisfaction level is 0.800. Thus, the common satisfaction of the goals is at the level of 0.732.

4. Conclusion

In this study, a mixed integer linear model for a multi-objective multi-echelon closed-loop GSC is proposed. In this model proposed, besides deciding on the establishment locations of warehouses and distribution centers, meeting customer demand is considered. Another factor that needs to be decided in the model is the type of transportation and the amount of transportation to be made. While making these decisions, the model sets an example for the GSC by considering both economic by minimizing cost, and environmental criteria by minimizing CO_2 emissions. In the model, the recycling procedure is also operated, so that some of the products from the customers are collected and separated, and reintegrated into production. In the solution phase of the model, a fuzzy approach has been implemented by using Zimmermann's "min" operator. Thus, a green closed-loop SC network has been designed, in which the objectives can meet at common satisfaction levels, although being contradictory each other in terms of being green or not, and as so are mutually compromised. An attempt has been made to draw attention to the importance of using recyclable raw materials or semi-finished products, using environmentally friendly modes of transportation in transportation between facilities, and ensuring that the facilities to be established are environmentally friendly. As a future direction, it is intended that our model will be developed in a way that will prevent monopoly in supplier selection, including combined transportation where environmentally friendly modes of transportation such as rail and sea are predominant.

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