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A methodology for the strategic design of reverse logistics networks and its application in the Turkish white goods industry

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In this study, a multi-objective model for the reverse logistics network design (RLND) problem and a novel methodology are proposed. The proposed methodology is comprised of two stages: the centralised return centre (CRC) evaluation stage and the reverse logistics network design (RLND) stage. In the first stage an integrated ANP and fuzzy-TOPSIS methodology is utilised. In the second stage, using the CRC weights obtained in the first stage, the RLND model is solved via genetic algorithms (GAs). The proposed methodology is applied to a case from the Turkish white goods industry. The results are discussed and analysed.

Keywords: MCDM; meta-heuristics; network design; reverse logistics

1. Introduction

Due to the escalating level of environmental problems, environmental initiatives enforced by governments, customers, or companies themselves have become an obligation. As part of these environmentally conscious initiatives, reverse logistics has received considerable attention from both academicians and practitioners. Tibben-Lembke and Rogers (1998) defined reverse logistics (RL) as "the process of planning, implementing and controlling the cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of origin for the purpose of recapturing value or proper disposal".

Usually, RL can be perceived as exactly the reverse of forward logistics (FL); however, in many decision-making areas, RL is not similar to FL (Tibben-Lembke and Rogers 2002). Since collecting and recovering products leads to numerous complications for logistical processes (Teunter 2001), RL may have different channels, collection points, decision-making units, product characteristics, etc. Considering the differences (Tibben-Lembke and Rogers 2002), there is a need to examine the RL concept as an independent research area. There has been extensive research in the literature on the RL segment since 1992. Fleischmann *et al.* (2000), Rubio *et al.* (2008), Guide and Wassenhove (2009), Pokharel and Mutha (2009) are some of the important studies that investigate the literature of RL from different perspectives. These papers may be referred to obtain more comprehensive information on the RL segment.

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Network design problem is one of the important research areas in RL segment with a big impact on profitability. In order to maximise the value recovered from used products, companies need to set up logistics structures that facilitate the arising goods flows in an optimal way. To this end, one needs to decide where to locate the various processes of the reverse supply chain and how to link them in terms of storage and transportation. In particular, companies need to decide how to collect recoverable products from their former users, where to inspect collected products in order to separate recoverable resources from worthless scrap, where to reprocess collected products to render them remarkable, and how to distribute recovered products to future customers (Dekker *et al.* 2003). When the current RL literature is investigated, there is an increasing focus on RLND problem. Some of the related studies are summarised as follows. Listeş (2007) presented a generic stochastic model for the design of networks comprising both supply and return channels, organised in a closed loop system. In this model, one objective, net cost minimisation is considered. Baros *et al.* (1998) proposed a two-level location for the sand recycling problem and consider its optimisation using heuristic procedures. In this study, total cost is tried to be minimised. Krikke *et al.* (1999) proposed a mixed integer linear programming model for net operating cost minimisation of a reverse logistics network. In this study, the authors first determined how return products are processed (recovery strategy) and subsequently they optimised the reverse logistics network. Beamon and Fernandes (2004) investigated a closed-loop supply chain in which manufacturers produce new products and remanufacture used products. They proposed a multi-period integer programming model which uses the present worth method to minimise total cost. Another cost minimisation model is proposed by Nagurney and Toyasaki (2005). In that study, an integrated framework for the modelling of reverse supply chain management of electronic waste is structured.

The above-mentioned RLND studies considered the problem for the optimisation of only one objective, mostly the cost minimisation objective. Naturally, in the RLND process, more than one objective has to be taken into account and, generally, the objectives conflict with each other. When the current RLND literature is examined, it can be seen from the literature that the multi-objective structure of the RLND process has not been investigated until recent years. However, nowadays there is an increasing attention to this scope and some of the recent studies can be summarised as follows. Pishvaee *et al.* (2010) developed a bi-objective mixed integer programming formulation to minimise total costs and maximise the responsiveness of a logistics network. They utilised from a multi-objective memetic algorithm to solve their model. The paper prepared by Sheu (2007) presented a coordinated reverse logistics management system for treatment of multi-source hazardous wastes in a given region. In this study, a linear multi-objective analytical model that minimises both the total reverse logistics operating costs and corresponding risks. In another paper, Sheu (2008) presented a multi-objective optimisation programming approach to address the issue of nuclear power generation. In this study, a linear multi-objective optimisation model is formulated to optimise the operations of both the nuclear power generation and the corresponding induced waste reverse logistics. The paper prepared by Du and Evans (2008) considered the cost and total tardiness minimisation objectives and utilised from a methodology consists of a combination of three algorithms: scatter search, the dual simplex method and the constraint method. Neto *et al.* (2009) designed an algorithm for the multi-objective linear problem with three objectives: minimise costs, cumulative energy demand and waste in a reverse logistics network. In this study, a multi-objective RLND problem is proposed. However, different from the abovementioned studies, in this study, centralised return centres' weighted assignments' maximisation and cost minimisation objectives are considered.

CRCs are processing facilities devoted to handling returns quickly and efficiently. In a centralised system, all products in the reverse logistics pipeline are brought to a central facility, where they are sorted, processed, and then shipped to their next destinations (Tibben-Lembke and Rogers 1998). According to Tibben-Lembke and Rogers (1998), constructing a CRC in a RLN may provide some benefits to the entire RLN from various sources: Simplified store procedures; improved supplier relationships; better returns inventory control; improved inventory turns; reduced administrative costs; reduced store-level costs; reduced shrinkage; refocuses on retailer core competencies; reduced landfill; improved management information.

Locating CRCs in the proper locations is an important problem and yields significant cost and time benefits to the entire RLN. Several authors have addressed the problem of locating collection centres from a RLND perspective (Min *et al.* 2006; Ko and Evans 2007; Aras *et al.* 2008; Aras and Aksen 2008). However, in these studies, the relative weights of CRCs were not considered. Tuzkaya and Gulsun (2008) evaluated CRCs taking into consideration qualitative factors, but the RLND process was not realised in that study. Integrating the evaluation of alternative CRC locations and the design of RLN has not previously been attempted in the RL literature. Additionally, as explained before, locating CRCs in proper locations is an important factor in RLND processes and qualitative factors should also be considered in this process. In this study, some criteria that cannot be considered quantitatively are integrated in the decision process considering the managerial judgements regarding these strategic decisions. These managerial judgements are formulated in terms of experiments and accounted by a weight factor assigned to CRCs. For the ultimate decision, also managerial experiments are utilised to weight the objective functions. The robustness of these values can also be checked through the factorial design, considering different levels for the management weights. This way, the relative qualitative effect of alternative CRC locations can be determined by the decision makers. Additionally, with varying the importance of each term in the objective function using sensitivity analyses the final decisions can be concluded. In this study, CRCs are evaluated with an ANP (Analytic Network Process)-fuzzy TOPSIS (Technique for Order Preferences by Similarities) approach and the assignments to the CRCs are weighted according to the evaluation results, and we have maximised the sum of the weighted assignments.

This paper proposes a new model and a new methodology for the RLND problem. In the model development phase, we utilised results from the above-mentioned studies, especially Min *et al.* (2006), Ko and Evans (2007), Aras *et al.* (2008) and Min and Ko (2008), interviews with the authorities from the manufacturing and logistics sectors. Additionally, an application from the Turkish white goods industry is presented in light of the lack of RL applications for cases from Turkey. A meta-heuristics approach, namely genetic algorithms (GA) is used to solve the proposed model. The proposed methodology and model are explained in Section 2, whereas the related application from the Turkish white goods industry is presented in Section 3 and the conclusions are given in Section 4.

2. Proposed methodology

In this study a novel methodology for the RLND problem is proposed. As can be seen in Figure 1, this methodology consists of five phases. Phase I is the initialising phase.

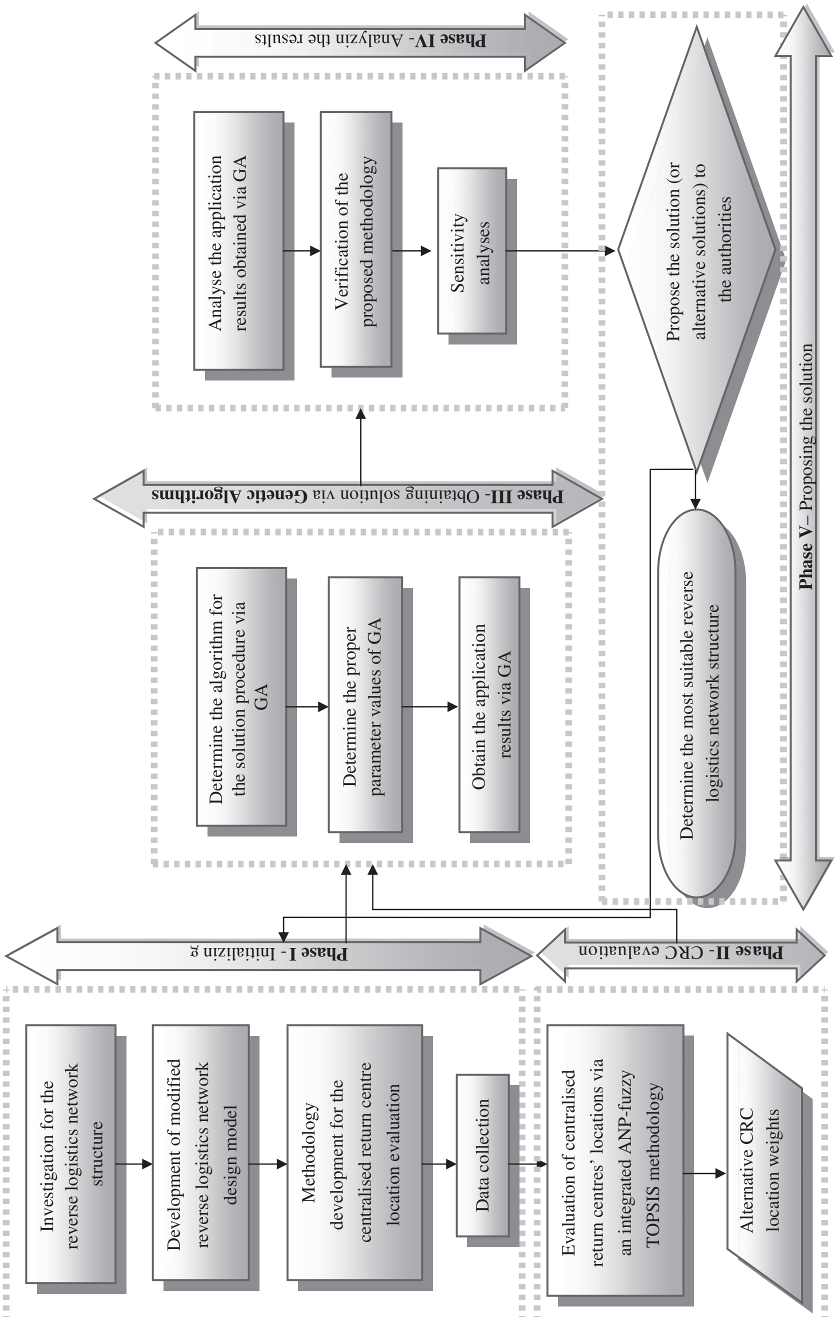

Figure 1. The proposed reverse logistics network design methodology.

In this phase, general information for the network is gathered and a RLND model is proposed. Moreover, a methodology is proposed for the evaluation of CRCs. In Phase II, utilising the proposed ANP-fuzzy TOPSIS methodology, alternative CRC locations are evaluated. Using the data obtained in Phases I and II, an algorithm is structured to solve the RLND problem in Phase III. In Phase IV, the results obtained are analysed and finally, in Phase V the results are presented for the authorities' approval. In this section, the proposed methodology is explained comprehensively with a summary of additional necessary mathematical background.

2.1 *The proposed reverse logistics network design model*

The reverse logistics network (RLN) consists of customers, initial collection centres (ICCs), centralised return centres (CRCs) and manufacturing facilities (MFs) (Figure 2). At the first stage, returned products are collected in the ICCs. ICCs are used only for collection purposes; the returns are not processed in any way in these centres. These centres may be any facility which is close to customers and has a spare area for storage. For instance, a washing machine manufacturer's ICC may be a seller of this product.

The products collected for a certain time in ICCs are sent to CRCs. In the CRCs, the returns are inspected and classified into three groups: scraps, disposal, and reusable parts. The inspection and classification process requires some money and time. In the classification phase, if the returned product or its component cannot be used as a new one, this part is sent to scrap or disposal. For disposal, a disposal cost is incurred. For scrap, there is a scrap income. The third class of products, containing reusable parts, is disassembled, overhauled, and sent to the MF. For the third class, disassembling and

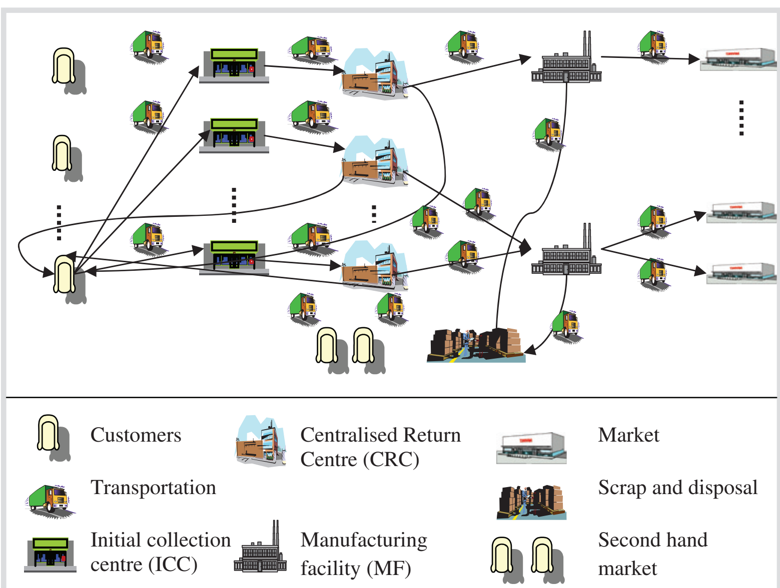

Figure 2. General structure of the reverse logistics network.

overhauling costs occur. In the ICC-CRC route determination phase, alternative CRC locations are evaluated via an ANP-fuzzy TOPSIS approach.

In the proposed model, reverse logistics network is designed separate from forward logistics. In the literature, there are some comments on the advantages and disadvantages of separate/integrated reverse logistics design (see Fleischmann 2001, Salema *et al.* 2010). The main advantage of the integrated approach is the synergy coming from common uses of resources, especially for the transportation. However, separate study is preferred when return quality, hazardous nature, and several other factors of return do not yield any benefit and only complicate the problem, Our initial reason for a separate study in our case is that the reverse logistics network is designed for a manufacturer which already has a structured forward chain. Mixing the return flow due to its disperse location and its quality is not desirable. Additionally, as Fleischmann (2001) mentioned if speed is an important factor for reverse logistics, the integration decision may not be rational.

Some assumptions are made for simplicity of the solution procedure and are listed below.

- From CRCs to MFs and disposal sites, products, wastes, and components are assumed to be sent daily and it is assumed that there are no handling costs.
- It is assumed that only one product type is considered in the system; however, in the real world, there would be more than one product type to be considered in a reverse logistics network structure.
- It is assumed that, for the scraps, the transportation costs are undertaken by the scrap dealer.
- For the MFs, there is no demand constraint for the returned products (or parts).
- In the CRCs, after classification, the products are disassembled. For calculation simplicity it is assumed that, after this phase, the same proportions are valid and can be used in calculations.

Table 1 shows the nomenclature of the modified model.

Two objectives are considered in the proposed RLND model: (1) net cost minimisation and (2) maximisation of weighted assignments to CRCs.

First objective: net cost minimisation

The first objective function is net cost minimisation (Equation (1)). This function includes transportation cost, ICC renting cost, CRC establishment cost, handling cost, inspection-classification-overhauling cost, and disposal cost. In addition, from these costs scrap income and reuse income are subtracted.

Minimise objective function 1 (OF1):

$$\begin{aligned}&\sum_{m=1}^{M}\sum_{i=1}^{I} TMd_{mi}X_{mi}TD+\sum_{i=1}^{I}\sum_{j=1}^{J} TMd_{ij}X_{ij}(TD/T_i)+\sum_{j=1}^{J}\sum_{k=1}^{K} TMd_{jk}X_{jk}TD\\&\quad+\sum_{j=1}^{J} TMd_{jB}Xl_{jb}TD+\sum_{m=1}^{M}\sum_{i=1}^{I} EB_iX_{mi}\left(\frac{(T_i+1)}{2}\right)TD+\sum_{i=1}^{I} Y_i\,R_i+\sum_{j=1}^{J} Z_j\,KM_j\\&\quad+\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}SM_j+\sum_{j=1}^{J} TDX_{jB}BM-\sum_{j=1}^{J}\sum_{k=1}^{K}\beta_H X_{jk}.GH-\sum_{j=1}^{J}\sum_{k=1}^{K}\beta_k X_{jk}.GUT \qquad (1)\end{aligned}$$

Table 1. Nomenclature.

Index	Description
Indices	
J	Index for CRCs $j \in J$
I	Index for ICCs $i \in I$
M	Index for customers $m \in M$
B	Index for disposal site
K	Index for manufacturing facilities (MFs) $k \in K$
Parameters	
TD	Annual working days
KM_j	Establishment cost of CRC_j
EB_i	Daily inventory carrying cost per unit for the ICCs
TM	Unit transportation cost of unit product (It takes different values according to transportation distance and the vehicle's loading situation (partial or full))
Arz_m	Daily supply volume of customer m
BM	Unit disposal cost
d_{mi}	Distance between customer m and ICC i
d_{ij}	Distance between ICC i and CRC j
d_{jk}	Distance between CRC j and MF k
d_{jB}	Distance between CRC j disposal site
K_i	Total capacity of ICCi for the working period
K_j	Total capacity of CRC j for the working period
GH	Unit scrap revenue
GUT	Unit gain obtained from re-using in the MFs
R_i	Renting cost of ith ICC for the working period
A_j	The weight of jth CRC obtained via ANP-fuzzy TOPSIS
SCA	Service coverage area for ICCs
SM_j	Inspection, classification and overhauling cost in the jth CRC
β_H	Scrap proportion of the products in CRC
β_B	Disposal proportion of the products in CRC
β_k	Reusable proportion of the products in CRC
C	Arbitrarily set large number
Variables	
Y_i	ICC's renting decision $Y_i \in \{0,1\}$
Z_j	CRC locations' establishment decision $Z_j \in \{0,1\}$
Y_{mi}	Customer m's assignment decision to ICC i $Y_{mi} \in \{0,1\}$
Z_{ij}	ICC i's assignment decision to CRC j $Z_{ij} \in \{0,1\}$
U_{jk}	CRC j's assignment decision to MF k $U_{jk} \in \{0,1\}$
T_i	Length of a collection period (in days) at ICC i
X_{jH}	Scrap volume of the products in CRC
X_{mi}	Daily product volume coming from customer m to ICC i
X_{ij}	Volume of products returned from ICC i to CRC j
X_{jk}	Reusable volume of the products in CRC
X_{jB}	Disposal volume of the products in CRC

The components of the first objective function can be explained as below. The total transportation costs from customers to the ICC, from the ICC to the CRC, from the CRC to the MF, and from the CRCs to disposal site can be represented as Equations (2)–(5), respectively.

$$\sum_{m=1}^{M}\sum_{i=1}^{I} TM d_{mi} X_{mi} TD \tag{2}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} TMd_{ij}X_{ij}(TD/T_i) \tag{3}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} TMd_{jk}X_{jk}TD \tag{4}$$

$$\sum_{j=1}^{J} TMd_{jB}X_{jB}TD \tag{5}$$

Total inventory handling costs for ICCs can be represented as Equation (6).

$$\sum_{m=1}^{M}\sum_{i=1}^{I} EB_iX_{mi}\left(\frac{(T_i+1)}{2}\right)TD \tag{6}$$

Total renting costs for selected ICCs can be represented as Equation (7).

$$\sum_{i=1}^{I} Y_i\,R_i \tag{7}$$

For the selected locations, establishment costs of the CRCs can be represented as Equation (8).

$$\sum_{j=1}^{J} Z_j\,KM_j \tag{8}$$

Total inspection, classification, and overhauling costs in CRCs can be represented as Equation (9), and total disposal costs can be represented as Equation (10).

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}SM_j \tag{9}$$

$$\sum_{j=1}^{J} TDX_{jB}BM \tag{10}$$

Total revenue obtained from scraps can be represented as Equation (11), whereas the income obtained from using used items in MFs can be represented as Equation (12).

$$\sum_{j=1}^{J}\sum_{k=1}^{K} \beta_H X_{jk}.GH \tag{11}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} \beta_k X_{jk}.GUT \tag{12}$$

Second objective: maximisation of weighted product volume assigned from ICCs to CRCs

The second objective function is the maximisation of the weighted product volume assigned from ICCs to CRCs (Equation (13)). Here, the weighting for the qualitative factors is realised for CRCs via ANP-fuzzy TOPSIS.

Maximise objective function 2 (OF2):

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}A_j\,(TD/T_i) \tag{13}$$

Constraints

Equation (14) tries to guarantee that each customer's demand is satisfied.

$$\sum_{i=1}^{I} X_{mi} = Arz_m \quad \forall m \in M \tag{14}$$

Equation (15) tries to guarantee that if an ICC is not rented, a customer cannot be assigned to this ICC.

$$Y_{mi} \leq Y_i \quad \forall m \in M \quad \text{and} \quad \forall i \in I \tag{15}$$

Equation (16) tries to guarantee that if a customer is not assigned to an ICC, an assignment product volume does not occur.

$$X_{mi} \leq CY_{mi} \quad \forall m \in M \quad \text{and} \quad \forall i \in I \tag{16}$$

Equation (17) tries to guarantee that the incoming product volume of the ICC is equal to the outgoing product volume of that ICC.

$$\sum_{m=1}^{M} X_{mi}TD = \sum_{j=1}^{J} X_{ij}(TD/T_i) \quad \forall i \in I \tag{17}$$

Equation (18) tries to guarantee that if a CRC is not established, an ICC cannot be assigned to this CRC.

$$Z_{ij} \leq Z_j \quad \forall i \in I \quad \text{and} \quad \forall j \in J \tag{18}$$

Equation (19) tries to guarantee that if an ICC is not assigned to a CRC, an assignment product volume does not occur.

$$X_{ij} \leq CZ_{ij} \quad \forall i \in I \quad \text{and} \quad \forall j \in J \tag{19}$$

Equation (20) tries to guarantee that the incoming product volume of the CRC is equal to the outgoing product volume from that CRC (to disposal, MFs, and scrap dealers).

$$\sum_{i=1}^{I} X_{ij}(TD/T_i) = \sum_{k=1}^{K} (X_{jk}TD) + X_{jB}TD + X_{jH}TD \quad \forall j \in J \tag{20}$$

The following equations (21, 22, 23) try to guarantee that a certain proportion ($\beta_k, \beta_H, \beta_B$) of the incoming product volume of the CRC is sent to the MF, scrap dealer or disposal, respectively.

$$\sum_{i=1}^{I} \beta_k X_{ij}(TD/T_i) = \sum_{k=1}^{K} X_{jk} TD \quad \forall j \in J \tag{21}$$

$$\sum_{i=1}^{I} \beta_H X_{ij}(TD/T_i) = X_{jH} TD \quad \forall j \in J \tag{22}$$

$$\sum_{i=1}^{I} \beta_B X_{ij}(TD/T_i) = X_{jB} TD \quad \forall j \in J \tag{23}$$

Equation (24) tries to guarantee that if a CRC is not assigned to a MF, an assignment product volume does not occur.

$$X_{jk} \leq CU_{jk} \quad \forall j \in J \quad \text{and} \quad \forall k \in K \tag{24}$$

Equation (25) tries to guarantee that each customer is assigned only one ICC, Equation (26) tries to guarantee that each ICC is assigned only one CRC and Equation (27) tries to guarantee that each CRC is assigned only one MF.

$$\sum_{i=1}^{I} Y_{mi} = 1 \quad \forall m \in M \tag{25}$$

$$\sum_{j=1}^{J} Z_{ij} = 1 \quad \forall i \in I \tag{26}$$

$$\sum_{k=1}^{K} U_{jk} = 1 \quad \forall j \in J \tag{27}$$

Equations (28) and (29) are the capacity constraints of the ith *ICC* and the jth *CRC*, respectively.

$$\sum_{m=1}^{M} X_{mi} TD \leq K_i \quad \forall i \in I \tag{28}$$

$$\sum_{i=1}^{I} X_{ij}\left(\frac{TD}{T_i}\right) \leq K_j \quad \forall j \in J \tag{29}$$

Equation (30) gives the service coverage area constraints of the ith *ICC*.

$$d_{mi} Y_{mi} \leq SCA \quad \forall m \in M \quad \text{and} \quad \forall i \in I \tag{30}$$

Equations (31)–(36) represent that some of the variables take only values above zero.

$$X_{mi} \geq 0 \quad \forall m \in M \quad \text{and} \quad \forall i \in I \tag{31}$$

$$X_{ij} \geq 0 \quad \forall i \in I \quad \text{and} \quad \forall j \in J \tag{32}$$

$$X_{jk} \geq 0 \quad \forall j \in J \quad \text{and} \quad \forall k \in K \tag{33}$$

$$X_{jB} \geq 0 \quad \forall j \in J \tag{34}$$

$$X_{jH} \geq 0 \quad \forall j \in J \tag{35}$$

$$T_i \geq 0 \quad \forall i \in I \tag{36}$$

Equations (37)–(41) represent that some of the variables take only values of 0 or 1.

$$Y_{mi} \in \{0, 1\} \quad \forall m \in M \quad \text{and} \quad \forall i \in I \tag{37}$$

$$Z_{ij} \in \{0, 1\} \quad \forall i \in I \quad \text{and} \quad \forall j \in J \tag{38}$$

$$U_{jk} \in \{0, 1\} \quad \forall j \in J \quad \text{and} \quad \forall k \in K \tag{39}$$

$$Y_i \in \{0, 1\} \quad \forall i \in I \tag{40}$$

$$Z_j \in \{0, 1\} \quad \forall j \in J \tag{41}$$

2.2 *Proposed ANP- fuzzy TOPSIS methodology*

In this paper, a methodology that integrates the ANP and fuzzy TOPSIS techniques is utilised. The idea of the integration of the ANP and TOPSIS techniques was first proposed by Shyur and Shih (2006) and Shyur (2006). Shyur and Shih (2006) presented the integrated approach for a strategic vendor selection problem. They first used ANP to obtain the relative weights of the criteria but not the entire evaluation process, reducing the large number of pair-wise comparisons required. They then used the modified TOPSIS function, which exploits a newly defined weighted Euclidean distance and aims to rank competing products in terms of their overall performance using multiple criteria. Shyur (2006) also used a very similar approach to a different problem named the commercial-off-the-shelf (COTS) evaluation and selection problem. This paper also utilises an integrated ANP and TOPSIS methodology for the centralised return centre (CRC) location evaluation problem of a reverse logistics network (RLN) design problem. ANP is preferred, since it provides the opportunity to consider the interdependencies between criteria. For computational simplicity, following the criteria evaluation phase, alternatives are evaluated via TOPSIS. However, the specific problem requires fuzzy numbers to be used due to the vagueness of the problem. Also, under many conditions, crisp numbered data are inadequate to model real-life situations since human judgments including preferences are often vague (Kannan *et al*. 2009). That is why the fuzzy version of TOPSIS is preferred. This methodology is firstly proposed by Tuzkaya and Gülsün (2008) and applied to a hypothetical study. The general flow of the methodology is shown in Figure 3. The details, calculation steps, basic information on ANP, TOPSIS and fuzzy sets can be found in Tuzkaya and Gülsün (2008). As a summary, this methodology starts with the ANP in which criteria weights are calculated considering interdependencies between them.

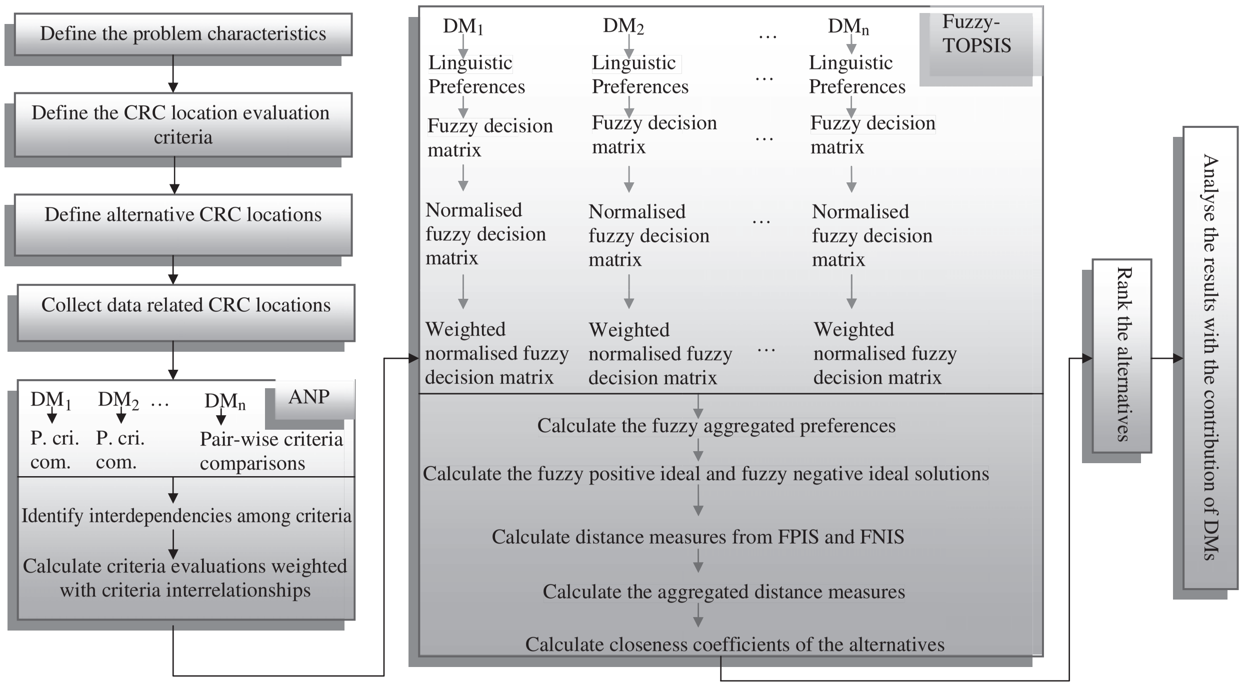

Figure 3. ANP-fuzzy TOPSIS methodology (Tuzkaya and Gülsün 2008).

Using the obtained criteria weights, alternative CRC locations are evaluated with the TOPSIS approach in the presence of linguistic vagueness.

2.3 *Genetic algorithms*

Following the first two phases, GA is utilised to solve the RLND problem. As mentioned in Ko and Evans (2007), such network design problems belong to the NP-hard class of problems and there are many papers that have used meta-heuristics because of the complex structure of the RLND process, such as Bautista and Pereira (2006), Min *et al.* (2006), Ko and Evans (2007), Aras *et al.* (2008), Aras and Aksen (2008), Lee and Dong (2008), Min and Ko (2008), Kannan *et al.* (2009), Lee *et al.* (2009), Lee and Chan (2009), Lee and Dong (2009), etc. In this study, the complexity of the model necessitates utilising from a meta-heuristic and GA is preferred to solve the model due to its effectiveness in finding better solutions generation by generation via its systematic operators, which provide improvements and variety in the solution population. With an increase in the size of the problem, for example in our case, not only two regions but also all regions of Turkey may be taken into account for future researches, an increase is expected for the complexity of the problem. Also, nonlinearities in the OF1 and some of the constraints have to be handled. Those nonlinearities are raised from the returned product collection period on the ICCs. Because of this situation, product volume sending from ICCs to CRCs is affected from the collection period. This affects some capacity constraints and OF1's transportation costs (from ICCs to CRCs) and inventory costs parts.

The GA approach was first proposed by Holland in the 1960s and was inspired by Darwin's theory of evolution (Konak *et al.* 2006). GAs are stochastic search techniques based on the mechanism of natural selection and natural genetics. GAs, as opposed to conventional search techniques, start with an initial set of random solutions called the population. Each individual in the population is called a chromosome, representing a solution to the problem at hand. A chromosome is a string of symbols; it is usually, but not necessarily, a binary bit string. The chromosome evolves through successive iterations, called generations. During each generation, the chromosomes are evaluated, using some measures of fitness. To create the next generation, new chromosomes, called offspring, are formed by either: (a) merging two chromosomes from the current generation using a crossover operator or (b) modifying a chromosome using a mutation operator. A new generation is formed by (a) selecting, according to fitness values, some of the parents and offspring and (b) rejecting others so as to keep the population size constant. Fitter chromosomes have higher probabilities of being selected. After several generations, the algorithms converge to the best chromosome, which hopefully represents the optimum or sub-optimal solution to the problem (Gen and Cheng 1997). Details of the steps in the GA search can be seen in Figure 4 and the details of the application of GAs can be found in the application stage.

GA used in the reverse logistics network design model

In the first stage of the GA solution procedure, customers are assigned to the closest ICC, considering the capacity constraints. In the second stage, the ICC-CRC assignment problem is solved and in the next stage, CRC-MF assignment problem is solved. In this study, customer-ICC and CRC-MF assignment problems are solved with a simple heuristic. For the customer-ICC assignment problem, customers are assigned to the

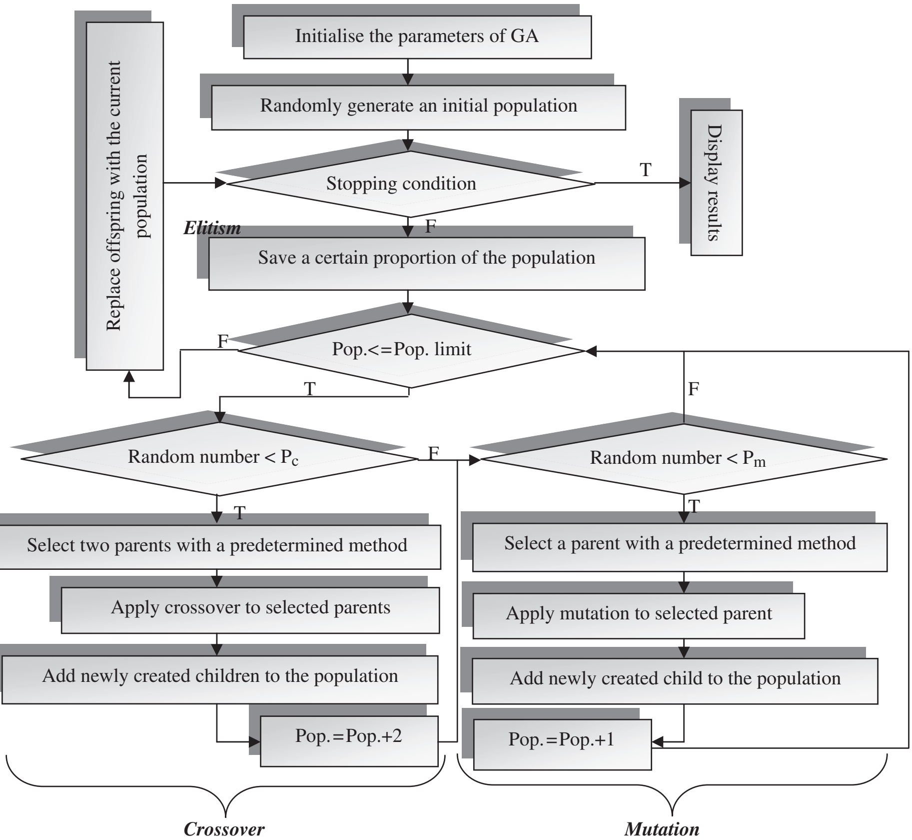

Figure 4. The general structure of genetic algorithms.

nearest ICC considering the capacity constraint. If there is not enough capacity for the nearest ICC, the second nearest ICC is tried, and the procedure continues until an assignment is done. For the CRC-MF assignment problem, a similar heuristic is applied. For this phase, it should be noted that; as stated in the model assumptions, it is assumed that there is no demand constraint for the MFs. For the last stage, total cost and weighted CRC assignments are calculated. Costs and weighted assignments are calculated as separate functions and, to satisfy the constraints, related punishments are added. At this stage, the calculated integrated function is the "fitness function". A punishment situation is realised when a constraint cannot be satisfied and, for each violation, a punishment value (here 1,000,000 has been selected) is added to the fitness function and this minimises the selection probability of the punished member.

Objective functions of the proposed model are integrated using the weighted sum method (WSM). WSM is a simple method for multi-objective optimisation problems. However, it guaranties to find a set of Pareto-optimal solutions. This guarantee does not exist for some of the other multi-objective optimisation techniques such as Goal Programming and Linear Physical Programming. If a goal program has alternative optimal solutions, some of them may not be efficient points of the corresponding multi-objective optimisation model (Rardin 1998). The same situation is valid for

ICC_1				ICC_2				...	ICC_{i-1}				ICC_i				CRC_1	…	CRC_j
1	0	1	0	0	0	0	0	...	1	1	1	0	0	0	0	0	0	…	1

Figure 5. An example of chromosome representation.

Linear Physical Programming. Utilised WSM is explained below. First of all, the model is solved via GA as if there is only one objective (OF1), and the best value for OF1 (BOF1) is obtained. The model is solved a second time via GA as if the only objective is OF2, and the best value for OF2 (BOF2) is obtained. Then expert opinions are obtained to find the weights of these two objectives: WOF1 (weight of OF1) and WOF2 (weight of OF2). Then an integrated objective function (IOF) is obtained as in Equation (42). Here OF1 is a minimisation function and OF2 is a maximisation function. In Equation (42), OF1 and OF2 represent the values of the related objective functions.

$$\mathrm{IOF} = \mathrm{WOF1} * \mathrm{OF1}/\mathrm{BOF1} + \mathrm{WOF2} * \mathrm{BOF2}/\mathrm{OF2} \tag{42}$$

Components of the GA process can be explained as follows:

Representation of the solution. To represent the solution, a similar chromosome representation is used to that of Min *et al.* (2006). The first part of each four-bit group represents the opening/closing decision for each ICC, i.e., "1" represents the opening decision, "0" represents the closing decision. The remaining three genes of the group represent the collection period in the ICCs. The last part of the chromosome is related to the opening/closing decisions of the centralised return centres (Figure 5). Additionally, information about the value of fitness function, customer-ICC assignments and CRC-MF assignments are embedded to the represented solution, i.e., as the member generated, assignments and fitness functions are calculated.

New member and population construction. The new member construction process can be seen in Figure 6. In the figure, "adjust the chromosome to standard form" can be explained as follows: if the chromosome's ICC part consists of n members, 4^*n $(n = 0, 1, \ldots, n)$, it is controlled if it is "0" or "1". If it is "1", there is no problem; however, if it is "0", and there is at least one "1" in the genes of 4^*n+1, 4^*n+2, 4^*n+3, this "1" (or "1"s) is converted to "0".

The feasibility control can be explained as follows: the ICC and CRC parts of the chromosome are controlled. If these two parts have at least one "1" individually, it means at least one ICC and one CRC are open and this situation shows the feasibility. If not, it means that the chromosome is not feasible and a new chromosome should be created. In this way, at least one ICC and CRC are open. Construction of the population is achieved by repeating the construction of a new member until the population size is reached.

Elitism. A certain part of the current population is transferred to the next generation. Elitism does not provide a variation to the next generation, but it prevents from deceiving the better fitness valued members. In this study, 5% of the current population is transferred to the next generation.

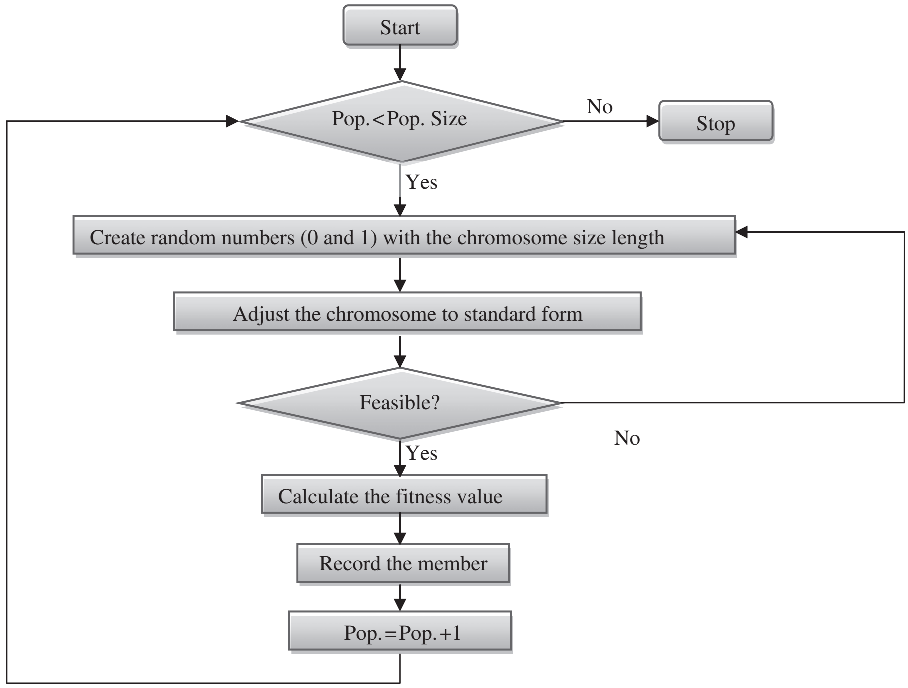

Figure 6. The new member construction process.

Parent selection. Three methodologies were tried for the parent selection procedure. In the first one, the parents are selected according to their fitness values using the roulette wheel technique. In this methodology, as the population size increases the chance to be selected decreases. In other words, as the population size increases, the procedure turns to random selection; however, the calculation intensity increases. In the second methodology, tournament selection is applied. This methodology is faster than the roulette wheel, but with the increase in tournament size it is observed that the possibility of finding local optimal solutions increases and the methodology reverts to an elitism methodology. In the third methodology, the parents are selected randomly. If the first parent is the same as the second, the random selection procedure is repeated. Then the selected parent is transferred to the crossover operator.

Crossover. Parents are selected from the current generation and considered for the crossover operator. In this study, a two-point crossover operator is utilised. Here, two points are randomly determined from each parent. These two points must be different and the first one should be smaller than the second one. Then, the sequence of the chromosome from the first parent between these two points is exchanged with the sequence of the second parent's chromosome between these two points. In this way, the first child is constructed. The second child is constructed in the opposite way. Then the children are adjusted to the standard form and, if these children are not feasible, the procedure is repeated. If they are feasible, their fitness values are calculated and they are transferred to the next generation.

Mutation. A similar procedure is used for the mutation operator as the crossover operator. A member is selected from the current population and transferred to the mutation operator. Then, a random point is determined for the mutation and the selected gene is changed to "0" if it is "1", and vice versa. The new member is changed to the standard form and, if it is not feasible, the procedure is repeated. If it is feasible, the fitness value is calculated and the new member is transferred to the next generation.

3. An application from the Turkish white goods industry

3.1 *The case of the Turkish white goods industry*

In the application phase, we interviewed experts from the Turkish white goods industry and logistics sector. General information was obtained from TURK-BESD (Turkish White Goods Manufacturers Association – www.turkbesd.org), Ekol Logistics (an important logistics company in Turkey that provides transportation for an important Turkish white goods manufacturer), and Arçelik A.Ş. (an important Turkish white goods manufacturer), as well as the Turkish Statistical Institute (TSI – www.tuik.gov.tr) and the Turkish General Directorate of Highways (TGDH – www.kgm.gov.tr).

In this study, a case from the Turkish white goods industry is investigated. For this case, real sales and seller data of a washing machine manufacturer (Manufacturer X) is utilised. Since there is a lack of real data on returned products for the white goods industry of Turkey, some deductions are made.

Based on our interviews with the experts from the abovementioned firms and institutions, expected returned washing machine volume for 2008 was 1,634,345 unit. Since real data for 2009 and 2008 cannot be obtained, returned washing machine volume is assumed to be the same as the 2008 expectations. However, according to the expert opinions, an important variation from this volume is not expected since washing machine sales and returns are relatively less uncertain considering the nature of the product, which is usually a function of general economic indicators.

Since Istanbul and Manisa are two important manufacturing locations in the Aegean and Marmara regions, it is assumed that a returned washing machine's reusable parts can be sent to the MFs in those locations. For these regions, İzaydaş's disposal site at Solaklar Village, Kocaeli, is found as the most proper disposal site. Additionally, Manufacturer X's seller network consists of 122 units. In this study, since it would not be possible to obtain information from each customer, the 122 districts are assumed to be customers. A sample of the daily supply information for these customers is given in Table 2.

Returned products from customers are collected in ICCs. In the process of selecting alternative locations for ICCs and determining their capacities and renting costs, population volumes (TSI 2009), return volumes (TURK-BESD 2009) and interviews with the authorities were utilised. The potential ICC locations, their capacities, and annual renting costs are given in Table 3.

The distances between the customers and ICCs (Table 4) were obtained from TGDH (2009).

Products are sent to CRCs from the ICCs. The alternative locations for CRCs are determined by considering expert opinions, population statistics, and return intensive locations. CRC establishment costs and proper capacities and inspection-classification-overhauling costs are also determined via interviews with experts (Table 5).

Table 2. Customers and their daily returns.

Center	# Customer	Customer	Daily return
Afyonkarahisar	1	Merkez	14
	2	Çay	2
	3	Dinar	3
	4	Emirdağ	3
Aydın	5	Didim	3
	6	Kuşadası	5
	7	Merkez	16
	8	Söke	8
Balıkesir	9	Ayvalık	7
	10	Bandırma	15
	11	Burhaniye	6
	12	Edremit	12
	13	Erdek	4
	14	Merkez	36
...	...	...	...
Tekirdağ	116	Çerkezköy	15
	117	Çorlu	25
	118	Merkez	18
	119	Malkara	6
Uşak	120	Merkez	15
	121	Ulubey	1
Yalova	122	Merkez	17

Table 3. Alternative ICC locations, ICC capacities and annual ICC renting costs.

#ICC	Location	ICC Capacity (unit/year)	ICC renting cost (TL/year)
1	Balıkesir (Merkez)	200,000	35,000
2	Bursa (Osmangazi)	200,000	50,000
3	Çanakkale (Merkez)	200,000	30,000
4	Denizli (Merkez)	200,000	35,000
5	Edirne (Merkez)	200,000	35,000
6	Istanbul (Kartal-Samandra)	200,000	60,000
7	Istanbul (Küçükçekmece-İkitelli)	200,000	65,000
8	Istanbul-Şişli	200,000	80,000
9	Izmir (Konak)	200,000	45,000
10	Kocaeli (Merkez)	200,000	50,000
11	Kütahya (Merkez)	200,000	25,000
12	Manisa (Merkez)	200,000	30,000
13	Muğla (Merkez)	200,000	25,000
14	Sakarya (Merkez)	200,000	40,000
15	Tekirdağ (Merkez)	2,000,000	40,000

Table 4. The distances between ICCs and customers.

#Customer \ # ICC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	321	250	528	225	689	338	377	361	327	349	100	309	370	592	312
2	313	213	335	445	280	336	374	361	333	295	293	301	335	301	449
3	318	338	503	113	681	425	464	450	340	385	185	313	232	397	584
4	319	254	508	596	598	342	381	365	401	301	101	307	328	622	501
5	332	476	424	225	637	601	640	624	157	619	422	184	120	523	672
6	273	416	364	185	577	542	582	565	98	560	372	125	157	464	613
7	293	422	455	126	664	498	538	522	130	570	415	156	99	635	601
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
120	278	311	389	152	634	325	365	349	211	390	141	193	297	605	353
121	268	300	379	142	624	320	360	340	200	380	135	185	290	595	345
122	216	69	323	568	405	41	81	64	387	65	236	351	606	308	102

Table 5. Alternative CRC locations, CRC establishment costs, capacities, unit inspection-classification and overhauling costs.

#CRC	CRC location	CRC establishment cost	CRC capacity (unit)	Inspection-classification-overhauling cost (unit/TL)
1	Bursa-Osmangazi	1,000,000	500,000	5.0
2	Istanbul-Anadolu-Samandıra	1,250,000	500,000	5.5
3	Istanbul-Avrupa-İkitelli	1,375,000	500,000	5.5
4	Denizli-Merkez	750,000	500,000	4.0
5	Izmir-Bornova	875,000	500,000	4.5

Table 6. Unit washing machine transportation costs.

Transportation distance (km)	Full transportation cost (km/TL)	Partial transportation cost (km/YTL)
<250	0.015	0.021
250–500	0.012	0.016
>500	0.010	0.014

The transportation costs change according to the transportation distance and whether the vehicle is partially or fully loaded (Table 6).

The distances between ICCs and CRCs (Table 7) and CRCs and other facilities (Table 8) were obtained from TGDH (2009).

As stated in the model development phase, in the CRCs, returned products are inspected and classified. In this phase, according to the expert opinions, %25 (β_k) of the returned products are re-usable parts and are sent to the MFs; %50 (β_H) of returned products are not re-usable and are sold as scraps; %25 (β_B) of the returned products are not re-usable and are sent for proper disposal option.

Table 7. Distances between ICCs and CRCs.

#ICC \ #CRC	1	2	3	4	5
1	151	269	307	288	170
2	0	219	258	437	379
3	271	409	275	495	272
4	437	452	490	0	231
5	420	267	223	697	484
6	218	0	50	450	438
7	258	51	0	490	478
8	242	34	26	474	462
9	322	44	482	224	4
10	132	151	119	538	456
11	173	239	278	289	212
12	286	409	447	206	32
13	541	597	635	145	204
14	375	170	127	668	361
15	159	135	173	501	510

Table 8. Distances between CRCs and the other facilities.

#CRC	Disposal facility (Kocaeli-Solaklar)	Washing machine manufacturing facility 1-İstanbul	Washing machine manufacturing facility 2-Manisa
1	161	112	285
2	90	44	408
3	127	11	368
4	416	479	202
5	464	398	36

Evaluating alternative locations for the CRCs

As mentioned earlier in this study, the proposed model has two objectives, one of which is related to the maximisation of the weighted assignments to the CRCs. In this objective, the assignments are weighted using the CRC weights which are obtained via an integrated ANP-fuzzy TOPSIS approach. In the CRC evaluation process, interviews are conducted with experts from different areas (Table 9).

In the next step, the criteria for evaluating CRC location alternatives, related attributes and relationships between them are determined according to the relevant literature (especially Karagianniadis and Moussiopoulos (1998), Mahler and De Lima (2003), Vasiloglu (2004), and Al-Jarrah and Abu-Qdais (2006), Tuzkaya *et al.* (2008) and Tuzkaya and Gülsün (2008)) and the DMs in the field, such as municipal and environmental organisations and disposal site and manufacturing site authorities (Figure 7) For more detailed description for the criteria sets and the relationships between criteria, refer to Tuzkaya and Gulsun (2008).

Following the criteria determining phase, DMs are asked to evaluate relationships between criteria sets and alternative CRCs for criteria sets linguistically. For this phase,

Table 9. Decision makers for the CRC evaluation process.

#Decision maker	Decision maker
DM1	Environmental organisations
DM2	Municipality
DM3	Customers
DM4	Manufacturers
DM5	CRC management

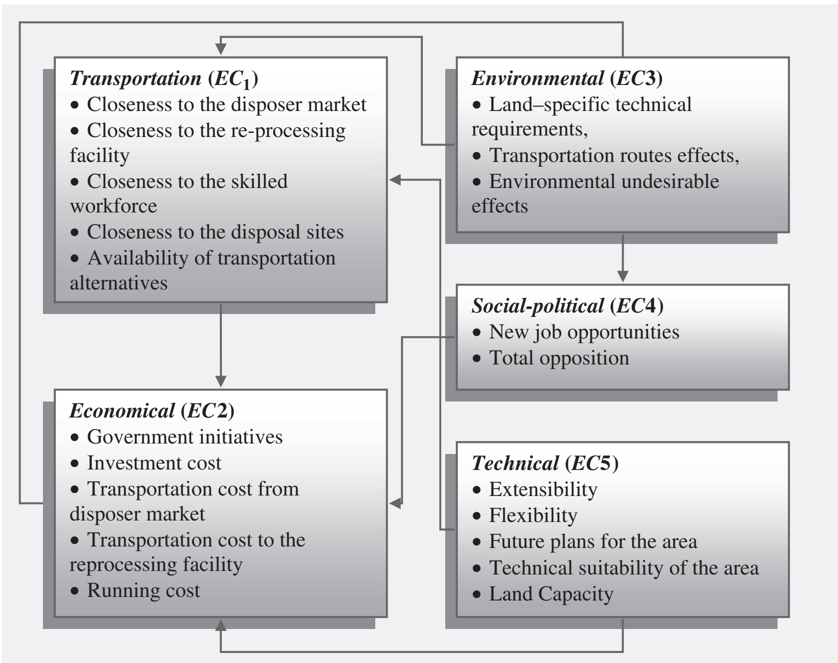

Figure 7. CRC evaluation criteria, the related attributes and the relationships between criteria (EC).

telephone and face to face interviews with DMs are performed to obtain evaluations of each DM group from different areas (Table 9). Whole CRC evaluations are realised by utilising the algorithm which is explained in Section 2.1 and Tuzkaya and Gülsün (2008). Closeness coefficients are calculated and presented in Table 10. For detailed information about the application of the methodology and calculation details, refer to Tuzkaya and Gülsün (2008). Here, the obtained closeness coefficients (CC) are used as the weight of alternative CRC locations (A_j).

As can be seen from Table 10, the best evaluation value (0.68) belongs to the CRC4 (Denizli-Merkez) location. CRC4 is the closest alternative to the positive ideal solution and furthest alternative to the negative ideal solution. This is because; CRC4 has the best evaluation results for the EC1, EC2, EC3 and EC5 criteria groups. Also, CRC4 is the second for the evaluations of the EC4 criteria group. As EC4's importance degree is

Table 10. CCs of alternative CRC locations.

	Positive distance (PD)	Negative distance (ND)	PD + ND	CC = ND/(PD + ND)
CRC1	0.61	0.37	0.98	0.38
CRC2	0.63	0.47	1.10	0.43
CRC3	0.33	0.45	0.78	0.58
CRC4	0.24	0.53	0.77	**0.68**
CRC5	0.62	0.25	0.87	0.28

the lowest among the other criteria group, it's affect on the results is negligible for the final ranking.

Solution of the model

Data collected for the application and CRC evaluations obtained via integrated ANP-fuzzy TOPSIS approach are utilised for the solution process of the model. As explained in Section 2, the problem is solved via GA. For the GA process, the parameters are determined via some analyses which are explained in Section 3.2. According to the analyses, the elitism rate of the GA is determined to be 5%, the crossover probability is 70%, the mutation probability is 10%, and the population size is 1250. For the GA process, a Visual Studio C# program was developed. Parameters used in GA are found as explained in Section 3.2.1. Utilising the parameters obtained as in the parameter analyses section, the proposed model is solved via GA. First of all, the DMs are asked to compare the objective function weights: the weight of OF1 is determined as 0.8 and that of OF2 as 0.2. Also, BOF1 and BOF2 values are obtained as 2464099 TL and 444990 units, respectively. To obtain a single objective function from these two objectives Equation (42) is utilised.

3.2 *Computational analyses*

3.2.1 *Parameter analyses*

In GA, to find the closest results to the optimum, it is very important to determine proper parameter values. In the parameter determination phase, various population sizes, elitism ratios, and crossover and mutation probabilities are tried. The problem is solved for one parameter change at a time. The experimental parameter values are determined by considering the related literature and for the population sizes 250, 500, 750, 1000, and 1250; elitism ratios 5%, 10%, 15%, and 20%; crossover probabilities 70%, 80%, and 90%; and mutation probabilities 1%, 5%, 10%, and 15%. Using all these values, 240 combinations are iterated 50 times. To select the appropriate parameter values, for each experiment the minimum, maximum, and average values, standard deviations, and solution times are considered. However, the average values are the key factor in determining the best values, since there are no significant differences for the other factors.

As illustrated in Figure 8, the parameter settings were varied individually. As the population size increased (Figure 8a), the results improved. The best values for the other parameters occur at 5% for the elitism ratio (Figure 8b), 70% for the crossover probability (Figure 8c), and 10% for the mutation probability (Figure 8d).

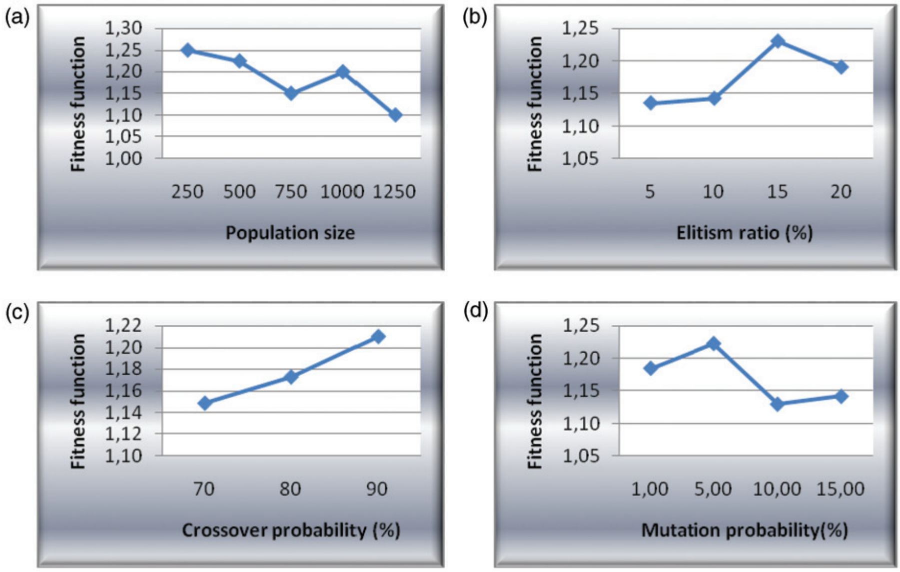

Figure 8. GA parameter settings. (a). Population size parameter settings. (b) Elitism ratio parameter settings. (c) Crossover probability parameter settings. (d) Mutation probability parameter settings.

3.2.2 *Application results*

When the model is solved via GA, and the RLN is designed as in Figure 9. The best chromosome representation obtained is as follows:

"0000 1000 1000 0000 1000 1000 0000 0000 0000 1000 1000 1000 1000 0000 1000 11010"

The result represented by the above chromosome has the fitness value of 1.0292 and, for this result, the value of OF1 is obtained as 2,464,100 TL and OF2 is obtained as 388,315 units. As can be seen from the chromosome, the ICCs represented by the numbers 2, 3, 5, 6, 10, 11, 12, 13, and 15 are determined to be rented, and the number of product waiting days are determined to be zero.

On the other hand, the CRCs represented by the numbers 1, 2, and 4 are determined to be established. CRC1 and CRC2 send their products or components to MF1, and CRC4 sends its products or components to MF2. Since there is only one disposal site, the established CRCs send their wastes to this disposal site (Figure 9).

As can be seen in Figure 9, assignments to ICC5 are more numerous than those of the other ICCs. Since the capacity constraint is not reached for any ICC, for this assignment, the most important factors are the maximum service area constraint and transportation costs. Number of returned products collection period in ICCs is determined to be zero. The collection period is mainly affected by the difference between full and partial transportation costs. With the current difference it is more beneficial to transport returned products daily. Since, this difference is not as much to make an effect, warehousing cost is the main factor for collection period length.

For the assignment from ICCs to CRCs, OF1 has more influence than OF2. This situation is realised parallel to the objective function weights, as can be expected. Thus, the maximum weighted CRC, CRC3, has no assignments and the lower weighted CRC,

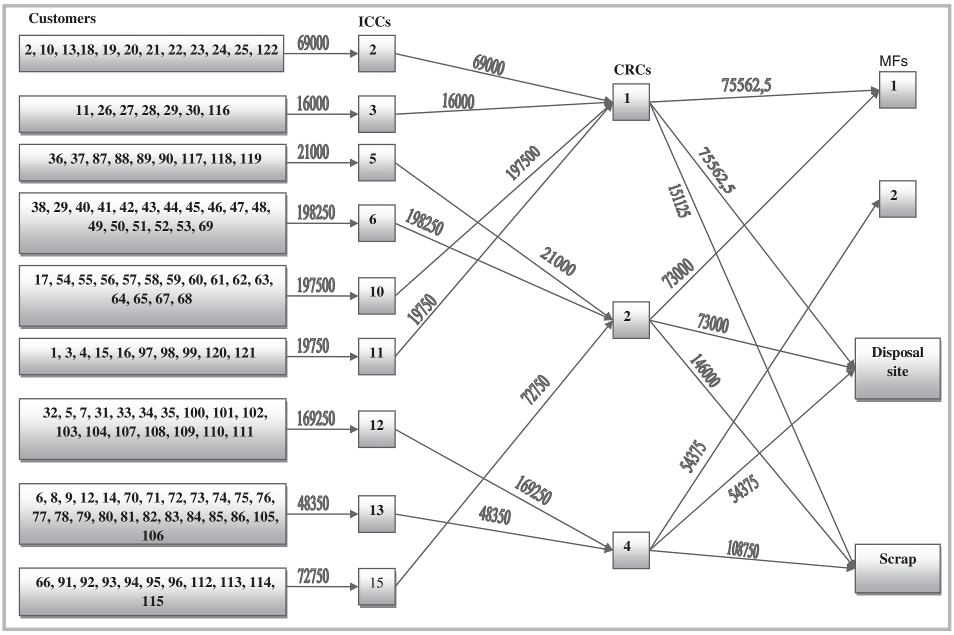

Figure 9. Designed RLN and assignment quantities.

CRC1, has the maximum assignment volume. This situation is expected to change with an increase in OF2 weights. Transportation cost minimisation is also the most important factor for the CRC-MF assignments since it is assumed that there is no demand constraint for the MFs. Related analyses will be given in the sensitivity analyses section.

It should be noted that for the above solution, there exist multiple Pareto optimal solutions in a problem if the objectives are conflicting with each other (Deb 2001). A solution is a Pareto optimal if no objective function can be improved without worsening at least one other objective function (Ho *et al*. 2002). In our model, there are two objectives which conflict with each other and the obtained solution is one of the Pareto optimal solutions with certain conditions like given objective function weights. One way to find a set of Pareto optimal solutions is to explore the solution space with a systematic variation of weight vector (Deb 2001). In this study, by changing the objective functions' weight vector, a set of the Pareto optimal solutions are found as shown in Figure 10.

3.2.3 *Sensitivity analyses*

In this study, sensitivity analyses have been performed to show the sensitivity of the results to some of the parameters and input data. In general, sensitivity analyses on the change in OFs' values with the change in WOFs; the change in the fitness function value with changes in the right hand sides of the constraints; the change in the assignments with the change in the CRC evaluation weights; and the change in the network structure with the change in the return volume, etc. have been performed. Expected changes have been observed with the changes of the parameters and input data. As examples of the performed sensitivity analyses, five representative analyses are explained.

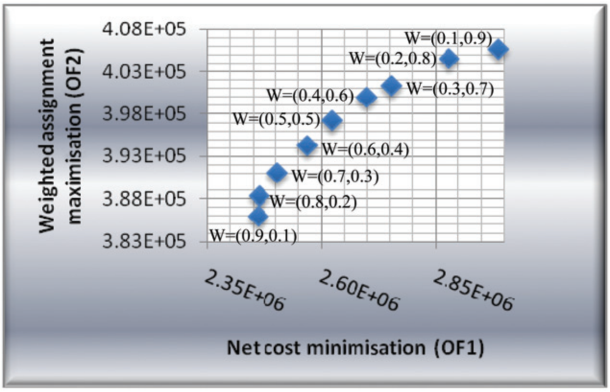

Figure 10. Pareto-optimal solutions for the variations of objective function weight vector (W = (WOF1, WOF2)).

As can be seen in Section 3.1., the objective function weights of the multi-objective model are determined via interviews with DMs. In this section, first of all, changes in the results with variations in the objective function weights are investigated. Figure 11a shows variations in the value of OF1 with changes in WOF1. As can be expected, a change in WOF1 from "0" to "1" improves the value of OF1 (cost minimisation); concurrently, as can be expected, the value of OF2 worsens and the fitness value improves to a certain value, then remains the same for a range, and then gets worse.

Another sensitivity analysis was conducted for the service coverage area constraint (Figure 11b). At the application phase, the service coverage area is determined to be 250 km by the DMs. If it is below 225 km, it is not possible to obtain feasible solutions. By extending the service coverage area, the fitness function improves. With the relaxation of this constraint, it may also be observed that the value of OF1 improves. However, since WOF2 is very low, there is no consistent increase or decrease in the value of OF2.

The third sensitivity analysis is conducted for the CRC capacity constraints. With relaxation of the capacity constraints, the values of the fitness function (Figure 11c) and OF1 improve. The impact on the value of OF2 is not clear because of the relatively low weight of OF2. A similar sensitivity analysis is conducted for the capacity of the first CRC, which is the most preferred one in terms of assignment volume. With the relaxation of the capacity constraint of the first CRC, the assignment volume to this facility increases to a certain point. After this point, the assignment volume is not affected by this relaxation with the impact of the service coverage area constraint.

The fourth sensitivity analysis is conducted for the length of the collection period in ICCs (Figure 11d). As can be seen from Figure 11d, with the increase in the difference between full and partial transportation costs, the length of the collection period in ICCs increases. For the current conditions, this difference's influence on the collection period length is not more than the warehousing cost's.

The last sensitivity analyses conducted for the change in the network structure with the change in the return volume (Figure 11e). It is observed that with an increase of 33% and more, it is impossible to find feasible solutions. The reason for this infeasibility is the service coverage area becomes constraint and with relaxations of this constraint feasible solutions can be obtained. Also, it can be said that current capacities of CRCs and ICCs

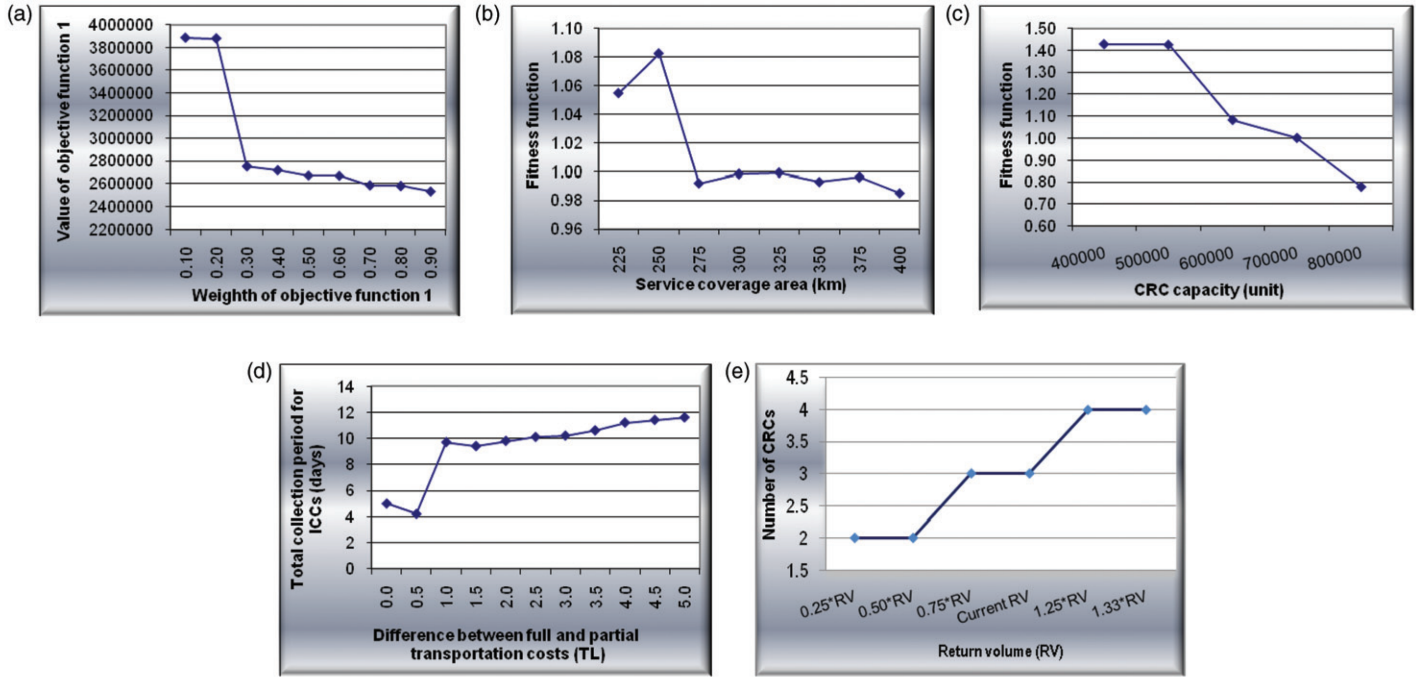

Figure 11. Sensitivity analyses. (a) The change in OF1 with changes in WOF1. (b) The change in the fitness function with changes in the service coverage area. (c) The change in the fitness function with changes in the capacity of the CRC. (d) The change in the total collection period in ICCs with the change in the difference between full and partial transportation costs. (e) The change in the number of established CRCs with the change in the return volume.

are not a problem for this level of increases. Additionally, according to expert opinions, this level of variation cannot be expected for the return volume.

4. Conclusions

Due to the escalating level of environmental problems, environmental initiatives, which are enforced by governments, customers, or companies themselves, have become an obligation. As part of environmentally conscious initiatives, reverse logistics has received considerable attention from both academicians and practitioners.

Reverse logistics network design (RLND) issues are an important part of the current literature on reverse logistics. In this study, a novel multi-objective model is proposed for the RLND problem. Generally, such network design problems belong to the NP-hard class of problems, and GA is preferred to solve the proposed model since GA is an effective methodology for finding better solutions generation by generation via its systematic operators, which provide improvements and variety in the solution population.

This study is unique among the current RLND literature for a variety of reasons. First of all, the proposed model considers the relative importance of the alternative CRC locations with an additional objective function being the cost minimisation function. Secondly, the use of integrated methodology (integrated MCDM-GA methodology) is unique for the RLND literature. Additionally, a novelty aspect about this paper is the classification phase in the CRCs, which has been considered in only a few studies in the literature. Additionally, applications of RLND in Turkey, especially for the Turkish white goods industry, have not been considered previously.

Considering the decision makers' preferences and characteristics of our case, a separate RLN is designed. Future research, depending on the nature of the problem may require an integrated investigation to maximise the utilisation of resources such as transportation, facility, labour, etc. However, one should not overlook the loss of flexibility in the forward chain, the effect of time pressure, and the increase of complexity in the managerial and organisational aspects.

Another notable issue is that uncertainty is an important characteristic of reverse logistics systems and usually stemming from variability associate with volume, quality and time of returns. Uncertainty degrees and types depends on the case under study, for instance, as in our case, the expected return volume variation may be relatively small for the products which have relatively long life-cycles. Such uncertainties can be studied through sensitivity analyses. However, other formats like in the case of short-product life cycle, may require a formulation and different fuzzy sets representing those variables in order to capture uncertainties inherent to that particular reverse logistics systems.

In this paper, two strategic level objectives are taken into account. As another future research direction is to include the tactical and operational level objectives related to for example production planning, inventory management in the model. In such a study, different level of objectives may be considered via a multi-level modelling approach.

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