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# Proposing a multi-objective multi-echelon closed-loop supply chain model with the possibility of partial disruption in distribution centers and maximizing network reliability

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**Abstract**

Nowadays, given the competitive environment of business world, designing a supply chain (SC) that is compatible with the needs of the consumer market seems crucial. Due to its long-term impact on the company's performance, making decisions related to fulfilling the customer demand is an important issue in SC design and management. The present research tries to design a closed-loop supply chain network (SCN) with possible partial disruption in distribution centers during servicing. The objectives of this model are to minimize the total cost of SCN and maximize the system reliability, which is, in turn, dependent on the strategy chosen to cope with the partial disruption. Thus, in case of a partial disruption, some centers should be selected to compensate for disruption that, in addition to reducing costs, will be able to increase the system reliability. A weighted goal programming approach is used for solving the proposed multi-objective model, and a non-dominated sorting genetic meta-heuristic algorithm along with the exact method are developed in order to solve the problem. The results indicated that the proposed algorithm has appropriate performance in achieving near-exact solutions in large scales problems.
**Keywords:** Closed loop multi-echelon supply chain, disruption, reliability, weighted goal programming

## 1-Introduction

A supply chain (SC), generally, embraces a set of activities in the flow and conversion of materials into products, such as supplying raw material and delivering the end products to the end users. Any SC mainly aims at fulfilling the customer needs with the highest possible efficiency and the lowest cost. In fact, structurally, the SC includes a network of retailers, wholesalers, distributors, manufacturers and suppliers (each acts as a downstream supplier and the retailer, in turn, meets the end customer needs).
Disruption in SC is unpredictable and unplanned that can disrupt the goods' and materials' normal flow in the SC, and thus, expose the companies within the SC to financial and operational risks. Generally, one can classify the majority of SC disruptions into three categories namely *supply-related disruptions, demand-related disruptions*, and *miscellaneous risks*. Supply-related disruptions take place when the supplier is unable to fulfill the orders timely. These risks can potentially disrupt the supply of products or services offered by the SC to its customers.

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Demand-related disruptions may occur due to a sudden drop or increase in the customer orders. These disruptions can potentially disrupt retail operations, and thus affect the ability of making products available to customers. Miscellaneous risks are those disruptions that can potentially influence the cost of business operations (Li and Ouyang, 2010).

The subject literature has employed new concepts of reliability to model the strategic behavior of distribution centers and customers in the network. Disruption in a center may be partial; this means that the disrupted center will still be able to give service at some of its original capacity. The lost capacity of the disrupted center shall be compensated by another undisrupted center. Here, part of the need is met by the center itself and the other part is provided by other centers. The ratio of the lost capacity of the disrupted center will depend on the initial investment in the design phase (Azad *et al.*, 2013b).

Because of the uncertain nature of SCs in the real world, the presence or absence of disruption and its magnitude are not predictable from the very beginning. Hence, it is necessary to control this phenomenon by adopting an appropriate approach. In this study, the partial disruption strategy is considered such that every center suffering from partial disruption will still be able to perform part of the service dedicated to it and the other part will be accomplished by another undisrupted center. This will be done in such a way that the reliability of the system (i.e. customer satisfaction) that arises from the supply of demand is maximized. In the meantime, to provide service in a partially disrupted center, a center will be selected that has the lowest total cost increase while enjoying the ability of covering the partially disrupted center. In this way, in addition to covering the partial disruption, reliability will be increased too. Consequently, when servicing to other centers, either there is no disruption at all, or if any (partial disruption), part of it will be covered by the center itself and the other part by another center so that the cost of the whole system will be minimized and the system reliability will be maximized.

The context of this paper is structured as follows: Section 2 reviews the related literature and determines the respective research gap. Problem description and proposed model are presented in section 3. Solution approaches are dealt with in section 4. The designed numerical examples are solved, the proposed algorithm is validated, and sensitivity analyses to important parameters are performed in section 5. Finally, conclusion remarks and further studies are presented in section 6.

## 2-Review of literature

This section deals with a review of related studies conducted separately in the proposed areas. To do this, the literature related to closed loop, forward and reverse SC with disruption were reviewed, and then SC studies with regard to reliability were investigated.

An important strategic decision in a supply chain network (SCN) design is SC type (forward, reverse or closed loop). Nobari, Kheirkhah and Esmaeili, (2016) examined an integrated closed loop SCN with regard to pricing, and designed a multi-objective model, including maximizing the profit of the entire network, minimizing the total returned products, and maximizing entrepreneurship. They further developed a meta-heuristic algorithm of colonial competition. Dondo and Méndez (2016) developed an operational planning model for forward and reverse logistics activities in a multilevel network. They investigated the problem of distribution and recovery, and for solving it, employed an analysis-based approach to achieve near-optimal solutions. Kayvanfar *et al.*, (2017) designed a water droplet algorithm for optimizing the problem of multi-echelon SC. The research objectives were to minimize logistics costs and maximize customer service level. The obtained results were compared with those obtained using NSGAII and NRGA methods. Mohammed *et al.*, (2017) investigated the issue of multi-period green closed loop SC under uncertain conditions. They employed a scenario-based method to cope with uncertainty. Fathollahi-Fard, Hajiaghaei-Keshteli and Mirjalili, (2018) also investigated the issue of developing a stochastic multi-objective closed loop SCN with social considerations in mind. There are several new meta-heuristic algorithms to better search the problem-solving corresponding space. Xu and Wang (2018) proposed a sustainable closed loop SC model with regard to emission and reproduction. Modak *et al.*, (2018) investigated the structure of a two-echelon closed loop SC considering quality, recycling and price. Hajiaghaei-Keshteli and Fathollahi Fard (2018) designed a sustainable closed loop SCN considering discounts, as well as economic, social and environmental indicators, simultaneously. They used a real industrial example in the glass industry to validate the proposed model. Reimann, Xiong and Zhou, (2019) proposed a closed loop SC model considering process innovation in reproduction. It was hypothesized that the cost of reproduction decreases with the innovation created in the production process. An integrated hybrid approach proposed by Govindan *et* *al.*, (2020) to design a closed loop SCN and select supplier rotation under uncertainty. They evaluated the proposed model by reviewing a real case study. Salehi-Amiri *et al.*, (2021) suggested a closed loop SCN for walnut and designed a mixed integer linear programming (MILP) aiming to cost reduction. To achieve the best answers, Taguchi approach was used to adjust the algorithm parameters. Gholizadeh *et al.*, (2021) adopted a robust optimization approach for a closed loop SC in the dairy industry. They designed a heuristic problem-solving model to reduce the time needed to solve large-scale problems. Fazli-Khalaf *et al.*, (2021) studied a resilient and sustainable closed-loop supply chain under uncertainty to maximize the coverage of customers' demand. Wang and Wan (2022) studied a multi-period multi-product green supply chain under uncertainty considering the demands depend on the product price and product greenness.

A newly introduced concept on the linkage of SC echelons deals with creating disruption in the relationship between the echelons (Chopra, Reinhardt and Mohan, 2007; Qi, Shen and Snyder, 2010(Qi, Shen and Snyder, 2010); Snyder *et al.*, 2006; and Singh *et al.*, 2011). For example, there may be a disruption when transferring products from distribution centers to customers, and it is not possible to fully supply a particular product by one or more distributors to one or more customers. To our knowledge, there is scarcity of studies conducted on the issue of designing SCN with disruption in the distribution centers. Azad *et al.*, (2013a) proposed a network considering disruptions in distribution centers and developed a second order cone-programming model to solve the model. Hatefi *et al.*, (2014b) developed an integrated reverse and forward reliable SCN with uncertainty and potential for equipment disruption conditions, and designed a fuzzy model for this purpose. Hatefi *et al.*, (2014a) in a similar other study, solved the same problem using the credibility-constrained mathematical programming. They generated several numerical problems and conducted sensitivity analysis to evaluate the proposed model's performance. In persuasion of previous studies, Hatefi and Jolai (2015) studied a reverse-forward reliable SCN in situations where equipment may be completely or partially disrupted. The purpose was to minimize the costs of equipment reopening, disruption, and transportation, as well as the costs of fines for unsatisfied demands. Torabi *et al.*, (2015) presented a probabilistic programming approach to develop a reliable closed loop SCN considering the probability of partial and general equipment disruption and uncertainty of the values of some parameters. The results indicated that operational risks and disruptions affect the whole structure of the designed network significantly. Hasani and Khosrojerdi (2016) investigated the issue of a robust SC under uncertainty and disruption conditions. They further employed the Lagrangian relaxation approach to assess the response efficiency as well as quality of the developed meta-heuristic method. Cui *et al.*, (2016) designed a reliable integrated SC model considering accelerating the transportation process under disruption risk conditions. Ivanov *et al.*, (2017) worked on the issue of SC with an emphasis on the environmental components like pollution and wastes under disruptive conditions. The computational results revealed that considering the recovery capacity may lead to the minimization of disturbances related to reverse flow in the SC. Jabbarzadeh, Haughton and Khosrojerdi, (2018) investigated the problem of closed loop SC under disruption conditions aiming to minimize the total cost of SC. For this purpose, they developed a robust stochastic optimization model. Furthermore, to check the model's performance, they applied real data from the glass production and distribution industry. Diabat, Jabbarzadeh and Khosrojerdi, (2019) designed a robust model for a perishable SC considering disruption possibility and system reliability. The purpose was to minimize the cost and duration to send the goods to clients post-crisis though there is a possibility of both equipment and route disruption between them. Sawik (2019) adopted a multi-basket approach to integrate SCs under disruptive risk situations. Lücker, Seifert and Biçer, (2018) concentrated on the issue of SC disruption risk using inventory and return capacity with uncertain demand. Yavari and Zaker (2020) investigated on a green closed loop SC resistant to perishable goods with the possibility of power grid and SC disruption. They integrated a SC with the power grid to cope with the power grid disruption. Hamdan and Diabat (2020) proposed a robust blood SCN at risk of disruption. For this purpose, they developed a two-stage robust optimization model considering random disruption in collection centers, blood banks and transportation routes. Gupta and Chutani (2020) investigated the financing SC considering pre-sales under disruption conditions. They assumed that disruption happens with a certain probability. Zhang, Diabat and Zhang, (2021) developed a reliable closed loop SC with the possibility of equipment failure, and proposed a non-convex mixed integer programming model. Kungwalsong *et al.*, (2021) developed a stochastic programming model for supply chain network under facility disruptions. In addition, a modified simulated annealing (SA) algorithm is developed to solve the problem. Esmizadeh and Mellat Parast (2021) studied a supply chain network considering competitive priorities and disruption. Aldrighetti *et al.*, (2021) studied a supply chain network models considering resilience and disruption. Sun *et al.*, (2022) developed a scnario-based robust optimization model for humanitarian logistics network considering disruptions to minimize the total deprivation and opration costs.

The literature review cleared that little research has been accomplished so far in the SC design phase considering reliability. The most important of them are as follows: as a pioneer in SC design considering reliability, Razmi, Zahedi-Anaraki and Zakerinia, (2013) designed a model for SCN re-design taking into account warehouse reliability. A multi-period multi-product multi-objective model was designed by Pasandideh, Niaki and Asadi, (2015) in order to develop a three-echelon SCN taking into account warehouse reliability. The aim was total cost reduction and increasing the average number of products sent to customers. He *et al.*, (2016) examined a logistics SCN in the automotive industry based on reliability. Rahmani and Mahoodian (2017) developed a SCN aiming to reduce carbon emissions considering the reliability and sustainability of facilities to cope with the parameter uncertain conditions. Diabat, Jabbarzadeh and Khosrojerdi, (2019) introduced a SCN for consumable goods taking into account disruption and reliability. The problem was based on a robust optimization approach for SC crisis management, with the aim of minimizing the cost and time of sending the goods to clients under critical conditions. Asim, Jalil and Javaid, (2019) designed an uncertain mathematical model for formulating a closed loop production-distribution SC taking into account the reliability of costs. Abbasi, Saboury, and Jabalameli (2021) studied a Reliable supply chain network considering disruption risk and product perishability. To solve uncertain model a credibility-based possibilistic programming is applied. Ebrahimi and Bagheri (2022) designed a multi-echelon network for the oil and gas supply chain to maximize the total profit and reliability of processing plants considering disruption.

In the present research, a closed loop SCN, consisting of four echelons (suppliers, manufacturers, distributors and customers) in the forward flow, and the three echelons (collection, disposal and recovery) in the return flow will be used. Given the characteristics of different levels, we will present several objectives, including minimizing costs and maximizing customer satisfaction through maximizing reliability. To our knowledge, the second objective function, i.e. reliability (due to its relationship with partial disruption), has not yet been dealt with in any previous study using this approach. Accordingly, this study is an attempt to propose a mathematical method for the problem of a closed loop SC design under partial disruption conditions in the distribution centers. The system reliability is related to the strategy selected to cope with the disruption. Thus, in case of a partial disruption occurrence, those centers should be chosen to compensate the amount of disruption that, in addition to reduce the costs, will be able to increase the system reliability too. This can be achieved by satisfying the customer demand, which has not been considered previously in such a way. In other words, choosing an appropriate strategy to cope with partial disruptions in SC for maximizing the network reliability is one of the main contribution of this research. Hence, a closed loop SCN with the probability of disrupted servicing in its distribution centers will be considered. To this end, an appropriate strategy must be adopted to cover the disruption to satisfy the goals of the system, including minimizing the total network costs and maximizing the system reliability.

## 3-Problem definition and proposed model

Here, we present a two-objective model to design a closed loop SC. The first and second objective functions aim to minimize the whole SC system costs and maximize the SC system reliability, respectively. This problem considers a closed loop SCN consisting of seven echelons (collection centers, disposal centers and recovery centers in the reverse SC and suppliers, production centers, distribution centers and customers in the forward SC). The proposed seven-echelon SCN is displayed in figure 1.

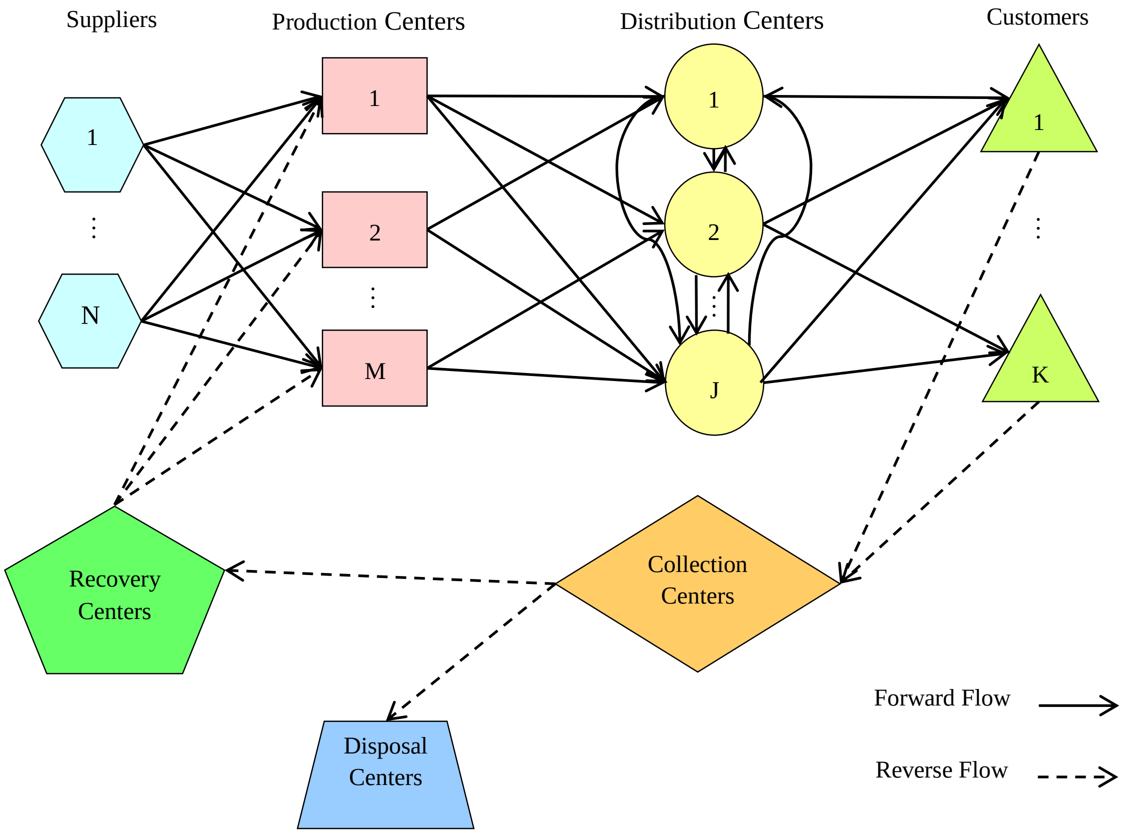


**Fig. 1.** Proposed SCN

As figure 1 illustrates, the first stage aims to detect the optimal locations of facilities at five echelons of production, distribution, collection, disposal and recovery, as well as determining the amount of products produced in the production centers, the amount of material supplied from suppliers, the amount of product sent from producers to the distributors, the amount of product sent from the distributors to customers, the amount of product returned to the collection centers from customers, the amount of product sent to the disposal centers from the collection centers, and finally, the amount of product recovered and sent from the recovery centers to the production centers. Simultaneous with these decisions and their associated variables, the network design must be accomplished in a way to minimize the SCN's total cost and maximize the system reliability. Also, since supplying operations throughout the network do not always work flawlessly enough, considering another goal alongside the main goal of increasing the reliability of distribution centers can results in a more practical model. On the other hand, as the capacity of each distribution center is limited, the expected time to failure (disruption) of distribution center i follows an exponential distribution with an average of $\sigma_i$; this failure may happen due to the occurrence of natural events, terrorist attacks, change of owners, worker-made mistakes, weather conditions etc. Consequently, the reliability of distribution center *i* in sending and distributing products to customers can be obtained as follows (Pasandideh, Niaki and Asadi, 2015):

$$R_i = P(T_i > \tau) = e^{-\sigma_i.\tau} \quad (1)$$

The average number of products sent by distribution center *j* to customer *i* is equal to $e^{-\sigma_i.\tau} X_{ji}$. Hence, in addition to considering the shipping costs that may affect the amount of products sent, the reliability of distributors is also one of the basic parameters in determining the amount of products sent.

## 3-1-Assumptions

The assumptions for developing a MILP include:

- The proposed SCN has seven different echelons as follows:
  - *Suppliers*
  - *Manufacturing centers*
  - *Distribution centers*
  - *Customers*
  - *Collection centers*
  - *Disposal centers*
  - *Recovery centers.*
- Decisions related to location are made at five echelons of manufacturing, distributing, collection, recovery and disposal centers.
- The capacity of various facilities and centers is limited and fixed.
- The costs of facilities' location and transportation units have been considered as constant.
- Several types of raw materials and final products have been considered.
- Any of the distribution centers (having a direct role in the SC) operates with disruption probability, i.e. the failure probability (operation malfunction) of each center follows an exponential distribution.
- Each raw material is used with a specific consumption coefficient in the production of the final product.
- Products imported to the recovery centers are converted into raw material with a special recovery factor.
- The probability of occurring partial disruption in the distribution centers has been considered.

## 3-2-Notations

In the following, the sets and indices, as well as the decision variables and parameters of the SC model are introduced:

**Indices and sets.**

$i$: Index of suppliers $(i \in I)$

$j$: Production centers index $(j \in J)$

$d$: Distribution centers index $(d \in D)$

$c$: Customers index $(c \in C)$

$m$: Collection centers index $(m \in M)$

$q$: Disposal centers index$(q \in Q)$

$o$: Recovery centers index ($o \in O$)

$s$: Raw materials index ($s \in S$)

$p$: Final products index ($p \in P$)

**Parameters.**

$D_{cp}$: Customer demand *c* for product *p*

$AR_{sp}$: Consumption coefficient of type *s* raw material for producing product *p*

$AD_{sp}$: Type *s* raw material required for producing product *p*

$AO_{spo}$: Recovery coefficient of product *p* to type *s* raw material in recovery center *o*

$SAC_{is}$: Capacity of supply center *i* to supply type *s* raw material

$PAC_{jp}$: Capacity of production center *j* to produce product *p*

$DAC_{dp}$: Capacity of distribution center *d* to distribute product *p*

$MAC_{mp}$: Capacity of collection center *m* to collect product *p*

$QAC_{qp}$: Capacity of disposal center *q* for product *p* disposal

$OAC_{op}$: Capacity of recovery center *o* to recover product *p*

$PSP_{ijs}$: Cost of transporting raw material *s* from supplier *i* to manufacturer *j*

$PPD_{jdp}$: Cost of transporting product *p* from manufacturer *j* to distributor *d*

$PDCr_{dcp}$: Cost of transporting product *p* from reliable distributor *d* to customer *c*

$PDCu_{dcp}$: Cost of transporting product *p* from unreliable distributor *d* to customer *c*

$PDC_{dd'p}$: Cost of transporting product *p* from reliable distribution center *d* to unreliable distribution center $d'$

$PCM_{cmp}$: Cost of transporting product *p* from customer *c* to collection center *m*

$PMQ_{mqp}$: Cost of transporting product *p* from collection center *m* to disposal center *q*

$PMO_{mop}$: Cost of transporting product *p* from collection center *m* to recovery center *o*

$POP_{ojs}$: Cost of transporting raw material *s* recovered from recovery center *o* to production center *j*

$\sigma_d$: Expected time to failure (disruption) of distribution center *d* following exponential distribution

$\tau$: Period of time during which the desired facility is not disrupted.

$Ad_{ij}$: Distance of supplier *i* and manufacturer *j*

$Bd_{jd}$: Distance of distribution center *d* and manufacturer *j*

$Cd_{dc}$: Distance of customer *c* and distribution center *d*

$Cdd_{dd'}$: Distance of distribution centers *d* and $d'$

$Dd_{cm}$: Distance of customer *c* and collection center *m*

$Ed_{mq}$: Distance of disposal center *q* and collection center *m*

$Fd_{mo}$: Distance of recovery center *o* and collection center *m*

$Gd_{oj}$: Distance of production center *j* and recovery center *o*

$\alpha_{pc}$: Flow rate of returned type *p* product from customer *c*

$\beta_p$: Flow rate of disposable product type *p* transferable from collection centers to disposal centers

$Pc_{jp}$: Product *p* production cost by manufacturer *j*

$Dc_{dp}$: Product *p* processing cost in distribution center *d*

$Mc_{mp}$: Product *p* processing cost in collection center *m*

$Qc_{qp}$: Product *p* processing cost in disposal center *q*

$Oc_{op}$: Product *p* processing cost in recovery center *o*

$Pf_j$: Production center *j* fixed erecting cost

$Mf_m$: Collection center *m* fixed erecting cost

$Qf_q$: Disposal center *q* fixed erecting cost

$Of_o$: Recovery center *o* fixed erecting cost

$fR_d$: Reliable distribution center *d* fixed reopening cost

$fU_d$: Unreliable distribution center *d* fixed reopening cost

$\pi_d$ : Probability of occurring disruption in unreliable distribution center *d*

$\alpha'$: Proportion of disrupted demand

*MA*: Optional big number

**Decision variables.**

$Px_{jp}$: Amount of product *p* manufactured by production center *j*

$Ax_{ijs}$: Amount of type *s* raw material transported from supply center *i* to production center *j*

$Aw_{ijs}$: Variable *zero and one*; if type *s* raw material is transported from supply center *i* to production center *j*, it will be equal to 1.

$Bx_{jdp}$: Quantity of product *p* transported from producer *j* to distribution center *d*

$Cx_{dcp}$: Amount of product *p* transported from distribution center *d* to customer *c*

$t_{dd'p}$: Amount of product *p* transported from reliable center *d* to unreliable center $d'$

$Dx_{cmp}$: Quantity of product *p* transported from customer *c* to collection center *m*

$Ex_{mqp}$: Quantity of product *p* shipped from collection center *m* to disposal center *q*

$Fx_{mop}$: Quantity of product *p* shipped from collection center *m* to recovery center *o*

$Gx_{ojs}$: Quantity of recovered raw material *s* transported from recovery center *o* to production center *j*

$Ay_j$: Variable *zero and one*; it is equal to one when production center *j* is established.

$Bry_d$: Variable *zero and one*; it is equal to one when reliable distribution center *d* is established.

$Buy_d$: Variable *zero and one*; it is equal to one when unreliable distribution center *d* is established.

$Bwr_{dc}$: Variable *zero and one*; if a product is transported to customer *c* from reliable distribution center *d*, it will be equal to 1.

$Bwu_{dc}$: Variable *zero and one*; if a product is transported to customer *c* from unreliable distribution center *d*, it will be equal to 1.

$Cy_m$: Variable *zero and one*; it is equal to one when collection center *m* is established.

$Dy_q$: Variable *zero and one*; it is equal to one when disposal center *q* is established.

$Ey_o$: Variable *zero and one*; it is equal to one when recovery center *o* is established.

## 3-3-Mathematical model

This section introduces a mathematical model proposed for the closed loop multi-echelon SC problem considering the disruption probability.
First objective function, minimizing the SC total cost, is defined as below:

$$\begin{aligned} Min\,Z_1 = {} & \sum_i \sum_j \sum_s Ad_{ij}\, PSP_{ijs}\, Ax_{ijs} + \sum_j \sum_d \sum_p Bd_{jd}\, PPD_{jdp} Bx_{jdp} + \\ & \sum_d \sum_c \sum_p Cd_{dc}\, PDCr_{dcp} Cx_{dcp} + \sum_d \sum_c \sum_p Cd_{dc}\, PDCu_{dcp} Cx_{dcp} + \\ & \sum_d \sum_{d' \neq d} \sum_p \pi_d Cdd_{dd'}\, PDC_{dd'p} t_{dd'p} + \sum_m \sum_c \sum_p Dd_{cm}\, PCM_{cmp}\, Dx_{cmp} + \\ & \sum_m \sum_q \sum_p Ed_{mq} PMQ_{mqp} Ex_{mqp} + \sum_m \sum_o \sum_p Fd_{mo}\, PMO_{mop}\, Fx_{mop} + \\ & \sum_o \sum_j \sum_s Gd_{oj} POP_{ojs}\, Gx_{ojs} \qquad (a) \end{aligned} \tag{2}$$

$$\begin{aligned} & + A\Big(\sum_j Pf_j Ay_j + \sum_d fR_d Bry_d + \sum_d fU_d Buy_d + \sum_m Mf_m Cy_m + \sum_q Qf_q\, Dy_q + \\ & \sum_o Of_o\, Ey_o\Big) \qquad (b) \end{aligned}$$

$$\begin{aligned} & + \sum_p \sum_j Pc_{jp}\, Px_{jp} + \sum_p \sum_d \sum_j Dc_{dp}\, Bx_{jdp} + \sum_c \sum_p \sum_m Mc_{mp} Dx_{cmp} + \\ & \sum_q \sum_m \sum_p Qc_{qp}\, Ex_{mqp} + \sum_o \sum_m \sum_p Oc_{op}\, Fx_{mop} \qquad (c) \end{aligned}$$

The first objective function aims to minimize the SC's total costs in three parts:
*a) Transportation costs at each stage of the forward and reverse SC*
*b) Location costs of all facilities at different echelons in the SC*
*c) Production and operating costs at distribution, collection, disposal and recovery centers.*
Parameter A is to scale the location cost versus other transportation, production and operating costs.
Second objective function, maximizing the SC reliability:

$$Max\,Z_2 = \sum_c \sum_p \sum_d e^{-\sigma_d . \tau}\, Cx_{dcp} \tag{3}$$

The second objective function deals with maximization of reliability, which is equivalent to maximizing the total volume of products sent by distribution centers to customers.

**Constraints.**

$$Px_{jp} \leq PAC_{jp}\, Ay_j \qquad \forall p, j \tag{4}$$

$$\sum_j Ax_{ijs} \leq SAC_{is} \qquad \forall s, i \tag{5}$$

$$\sum_p Bx_{jdp} \leq DAC_{dp}(Bry_d + Buy_d) \qquad \forall d, p \tag{6}$$

$$\sum_c Dx_{cmp} \leq MAC_{mp}\, Cy_m \qquad \forall m, p \tag{7}$$

$$\sum_m Ex_{mqp} \leq QAC_{qp}\, Dy_q \qquad \forall q, p \tag{8}$$

$$\sum_m Fx_{mop} \leq OAC_{op}\, Ey_o \qquad \forall o, p \tag{9}$$

$$\sum_i \sum_j Ax_{ijs} + \sum_o \sum_j Gx_{ojs} \leq \sum_p AD_{sp} \qquad \forall s \tag{10}$$

$$\sum_s \left(\sum_o Gx_{ojs} + \sum_i Ax_{ijs}\right) AR_{sp} = \sum_d Bx_{jdp} \qquad \forall j, p \tag{11}$$

$$\sum_j Bx_{jdp} + \sum_{d' \neq d} t_{dd'p} = \sum_c Cx_{dcp} + \sum_{d' \neq d} t_{dd'p} \qquad \forall d, p \tag{12}$$

$$\sum_m Dx_{cmp} = \alpha_{pc} \sum_d Cx_{dcp} \qquad \forall p, c \tag{13}$$

$$\sum_q \sum_m Ex_{mqp} = \beta_p \sum_c \sum_m Dx_{cmp} \qquad \forall p \tag{14}$$

$$\sum_o \sum_m Fx_{mop} = \left(1 - \beta_p\right) \sum_c \sum_m Dx_{cmp} \qquad \forall p \tag{15}$$

$$\sum_j Gx_{ojs} = AO_{spo} \sum_m Fx_{mop} \qquad \forall s, p, o \tag{16}$$

$$Ax_{ijs} \leq MA\ (Aw_{ijs}) \qquad \forall i, j, s \tag{17}$$

$$Cx_{dcp} \leq MA\ (Bwr_{dc} + Bwu_{dc}) \qquad \forall d, c, p \tag{18}$$

$$\sum_d Bwr_{dc} + Bwu_{dc} = 1 \qquad \forall c \tag{19}$$

$$\sum_d Bry_d \geq 1 \tag{20}$$

$$\sum_d Bx_{jdp} \leq Px_{jp} \qquad \forall j, p \tag{21}$$

$$t_{dd'p} \leq Bry_d MA \qquad \forall d, d', p \tag{22}$$

$$t_{dd'p} \leq Buy_{d'} MA \qquad \forall d, d', p \tag{23}$$

$$\sum_{d' \neq d} t_{dd'p} = Bwu_{dc} \alpha Cx_{dcp} \qquad \forall d, c, p \tag{24}$$

$$\sum_{d} Cx_{dcp} \geq D_{cp} \qquad \forall d, c, p \tag{25}$$

$$Ay_j, Bry_d, Buy_d, Cy_m, Dy_q, Ey_o, Aw_{ijs}, Bwr_{dc}, Bwu_{dc} \in \{0,1\};$$
$$Px_{jp}, Ax_{ijs}, Bx_{jdp}, Cx_{dcp}, Dx_{cmp}, Ex_{mqp}, Fx_{mop}, Gx_{ojs}, t_{dd'p} \geq 0 \tag{26}$$

Equation (4) shows the capacity limit of each production center to produce the desired product. Equation (5) displays the capacity limit of suppliers to supply raw materials. Equation (6) indicates the capacity limit of distribution centers to distribute products to customers. Equation (7) represents the capacity limit of collection centers to collect returned products from customers. Equation (8) shows the capacity limit of disposal centers for processing and disposal of products sent from collection centers. Equation (9) indicates the capacity limit of recovery centers to process and retrieve products sent from collection centers. Equation (10) displays the volume limit of raw materials required to produce final products. Equation (11) shows the equilibrium relationship between the volumes of materials entering production centers, which must equal the volume of final products dispatched from that production center to distribution centers according to the consumption coefficient of raw materials. Equation (12) shows the equilibrium relationship of volume of materials incoming to distribution centers, which should be equal to the volume of products dispatched from that distribution center. Equation (13) explains the equilibrium relationship between the volumes of materials entering collection centers, which must equal the volume of products returned from customers. Equation (14) indicates the equilibrium relationship between the volumes of materials entering disposal centers, which must be equal to the volume of products dispatched by collection centers. Equation (15) indicates the equilibrium relationship between the volumes of materials entering recovery centers, which must be equal to the volume of products sent by collection centers. Equation (16) indicates the equilibrium relationship of volume of materials sent to the production centers from the recovery centers, which should be equal to a certain volume of products sent back by the desired recovery centers. Equation (17) specifies the relationship between the decision variable of allocation of production centers to suppliers to meet the demand for raw materials with the decision variable of the volume of raw materials sent. Equation (18) identifies the relationship between the decision variable of customer allocation to distribution centers to fulfill the demand for products with the decision variable of the volume of products sent. Equation (19) indicates that every single customer should be assigned to one distribution center only. Equation (20) implies that there is at least one reliable distribution center in SCN. As shown in equation (21), the amount of product shipped to distribution centers should not exceed its production volume. Equations (22) and (23) explain that the product is transferred between two centers when both centers are reopened. Equation (24) shows the amount of products supplied from other reliable distribution centers to an unreliable distribution center. Equation (25) indicates that the volume of product dispatched to customers should at least equal to their demand. Equation (26) specifies the type of problem decision variables.

## 4-Proposed solution approaches

As already stated, the first objective function of the model is of cost type, and the second function deals with determining the SC reliability. Hence, to solve such problems, one can make use of multi-objective solution approaches. In multi-objective programming problems, usually more than one objective function exists, and there is not a single optimal solution having the potential to simultaneously optimize all objective functions; therefore, there exists usually a set of answers to the problem, called the *Pareto answer*. Among the conventional methods for solving exact multi-objective programming, one can mention the *weighted sum*, *Epsilon constraint*, and *goal programming* approaches. In this study, the goal programming approach has been used. The next section will present the reason for using this approach and its solution mechanism.

### 4-1-Weighted goal programming

One of the most important multi-objective models is *goal programming*, which was introduced by Charnes and Cooper, (1977). It has recently been studied by several researchers to cope with the multi-objective nature of optimization models and reveals a high capability. This approach was first proposed to solve systems with conflicting and multiple goals. The proposed methods of *goal programming* have a common context, all aiming to minimize unfavorable deviations from the goals. The advantage of goal programming over linear planning is consideration of different goals. In addition, the permissibility of deviating from goals can lead to flexibility in the decision-making process.

The general model of *weighted goal programming* approach is as follows:

$$\begin{aligned}
&\text{Minimize} \sum_{y=1}^{Y} \frac{W_y}{b_y}\left(d_y^+ + d_y^-\right)\\
&s.t.\\
&h_k(X) = (\leq \text{ or } \geq) 0 \qquad k = 1,2,\dots,q\\
&f_y - d_y^+ + d_y^- = b_y \qquad y = 1,2,\dots,Y\\
&d_y^+, d_y^- \geq 0 \qquad y = 1,2,\dots,Y
\end{aligned} \tag{27}$$

Positive deviations in the cost-type goals and negative deviations in the profit-type goals should be minimized. However, all deviations are, generally, maintained in the final goal function. In equation 27, $f_y$ is the amount of objective function *y*, $h_k(X)$ is the system's *k* constraint, and $b_y$ is its *y* goal. Negative and positive deviations' values are achievable from the goals as below:

$$\begin{aligned}
d_y^- &= \begin{cases} b_y - f_y & \text{if } f_y < b_y \\ 0 & \text{otherwise} \end{cases}\\
d_y^+ &= \begin{cases} f_y - b_y & \text{if } f_y > b_y \\ 0 & \text{otherwise} \end{cases}
\end{aligned} \tag{28}$$

In addition, $w_y$ represents the positive weighting coefficients that determine the importance of each goal relative to others. It is worth noting that weight coefficients are determined experimentally and according to the experts' opinions; the sum of these coefficients is equal to one ($\sum_y W_y = 1$).

### 4-2-Weighted goal programming of proposed model

Based on what mentioned above and according to the mathematical formulations, the final model proposed to solve the problem is as below:

$$\text{Minimize}\left(\frac{w_1}{b_1}(d_1^+ + d_1^-)\right) + \left(\frac{w_2}{b_2}(d_2^+ + d_2^-)\right) \tag{29}$$

$$\sum_{i}\sum_{j}\sum_{s} Ad_{ij}\, PSP_{ijs}\, Ax_{ijs} + \sum_{j}\sum_{d}\sum_{p} Bd_{jd}\, PPD_{jdp} Bx_{jdp}$$
$$+ \sum_{d}\sum_{c}\sum_{p} Cd_{dc}\, PDCr_{dcp} Cx_{dcp} + \sum_{d}\sum_{c}\sum_{p} Cd_{dc}\, PDCu_{dcp} Cx_{dcp}$$
$$+ \sum_{d}\sum_{d\prime\neq d}\sum_{p} \pi_d Cdd_{dd\prime}\, PDC_{dd\prime p} t_{dd\prime p}$$
$$+ \sum_{m}\sum_{c}\sum_{p} Dd_{cm}\, PCM_{cmp}\, Dx_{cmp} \tag{30}$$
$$+ \sum_{m}\sum_{q}\sum_{p} Ed_{mq} PMQ_{mqp} Ex_{mqp}$$
$$+ \sum_{m}\sum_{o}\sum_{p} Fd_{mo}\, PMO_{mop}\, Fx_{mop}$$
$$+ \sum_{o}\sum_{j}\sum_{s} Gd_{oj} POP_{ojs}\, Gx_{ojs} - d_1^{+} + d_1^{-} = b_1$$

$$\sum_{c}\sum_{p}\sum_{d} e^{-\sigma_d.\tau}\, Cx_{dcp} - d_2^{+} + d_2^{-} = b_2 \tag{31}$$

Equations (4) - (26).

Now to find the values of $b_1$ and $b_2$, we run the model with both of the objective functions, separately. Then we will solve the final model by placing these values and considering some weights for the two objective functions. Next section deals with how to produce sample problems and the results obtained via solving them using solution approaches.

## 5-Numerical examples and computational results

We have designed several sample problems to evaluate the proposed model. Table 1 presents the problem size information, and table 2 reports the range of the problem parameters. It is worth noting that the problem parameters have been generated randomly according to a uniform distribution.

**Table 1.** Scales of sample problems

| *Example* | $\|I\|$ | $\|J\|$ | $\|D\|$ | $\|C\|$ | $\|M\|$ | $\|Q\|$ | $\|O\|$ | $\|S\|$ | $\|P\|$ |
|---|---|---|---|---|---|---|---|---|---|
| *1* | *2* | *4* | *6* | *10* | *2* | *2* | *2* | *2* | *2* |
| *2* | *3* | *5* | *7* | *15* | *3* | *3* | *3* | *3* | *3* |
| *3* | *4* | *6* | *8* | *20* | *5* | *5* | *5* | *5* | *5* |
| *4* | *5* | *8* | *10* | *30* | *6* | *6* | *6* | *6* | *6* |
| *5* | *6* | *10* | *12* | *40* | *7* | *7* | *7* | *7* | *7* |
| *6* | *8* | *12* | *15* | *50* | *8* | *8* | *8* | *8* | *8* |

**Table 2.** Range of problem parameters

| | | | |
|---|---|---|---|
| $D_{cp}$ | uniform(100,150) | $PMQ_{mqp}$ | uniform(6,12) |
| $AR_{sp}$ | uniform(0.1,0.2) | $PMO_{mop}$ | uniform(6,12) |
| $AD_{sp}$ | uniform(2000,3000) | $POP_{ojs}$ | uniform(6,12) |
| $AO_{spo}$ | uniform(0.3,0.5) | $\sigma_d$ | uniform(12,15) |
| $SAC_{is}$ | uniform(60000,120000) | $\tau$ | uniform(0.001,0.005) |

Table 2. Continued

| | | | |
|---|---|---|---|
| $PAC_{jp}$ | uniform(60000,120000) | $Ad_{ij}$ | uniform(1,3) |
| $DAC_{dp}$ | uniform(8000,10000) | $Bd_{jd}$ | uniform(1,3) |
| $MAC_{mp}$ | uniform(6000,12000) | $Cd_{dc}$ | uniform(1,3) |
| $QAC_{qp}$ | uniform(6000,12000) | $Cdd_{dd'}$ | uniform(1,3) |
| $OAC_{op}$ | uniform(6000,12000) | $Dd_{cm}$ | uniform(1,3) |
| $PSP_{ijs}$ | uniform(6,12) | $Ed_{mq}$ | uniform(1,3) |
| $PPD_{jdp}$ | uniform(6,12) | $Fd_{mo}$ | uniform(1,3) |
| $PDCr_{dcp}$ | uniform(6,12) | $Gd_{oj}$ | uniform(1,3) |
| $PDCu_{dcp}$ | uniform(6,12) | $\alpha_{pc}$ | uniform(0.05,0.1) |
| $PDC_{dd'p}$ | uniform(6,12) | $\beta_p$ | uniform(0.1,0.12) |
| $PCM_{cmp}$ | uniform(6,12) | $Pc_{jp}$ | uniform(2,4) |
| $Dc_{dp}$ | uniform(2,4) | $Mc_{mp}$ | uniform(2,4) |
| $Qc_{qp}$ | uniform(2,4) | $Oc_{op}$ | uniform(2,4) |
| $Pf_j$ | uniform(1000000,2000000) | $Mf_m$ | uniform(100000,200000) |
| $Qf_q$ | uniform(100000,200000) | $Of_o$ | uniform(100000,200000) |
| $fR_d$ | uniform(30000,40000) | $fU_d$ | uniform(10000,20000) |
| $\pi_d$ | uniform(0.01,0.05) | $\alpha'$ | uniform(0.05,0.1) |
| $MA$ | 10000000 | A | $10^{-5}$ |

## 5-1-Exact solution of sample problems

Each of the above problems has been implemented and resolved using GAMS software. The output obtained from solving the sample problems is displayed in table 3.

Table 3. Results of solving sample problems using GAMS

| Example | Objective function 1 | Objective function 2 | Time (s) | Goal 1 | Goal 2 |
|---|---|---|---|---|---|
| 1 | 236247 | 2886 | 4.65 | 236247 | 18086 |
| 2 | 238377 | 6491 | 5.07 | 237404 | 25418 |
| 3 | 356531 | 15230 | 11.56 | 356531 | 43446 |
| 4 | 443895 | 26072 | 18.05 | 441649 | 47612 |
| 5 | 590722 | 39630 | 29.15 | 590552 | 56764 |
| 6 | 694614 | 58211 | 48.10 | 694608 | 67884 |

Figure 2 illustrates the way of changing the time to solve the problems in different scales.

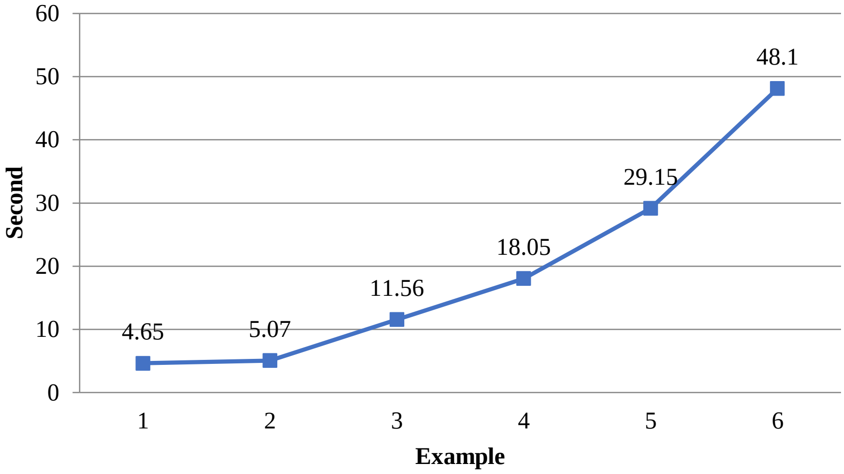


**Fig. 2.** Solution time for sample problems using exact method

As shown, as dimensions of the problem increases, the solution time increases exponentially. According to Bozorgi Atoei, Teimory and Amiri, (2013), being Np-Hard type, the above problem cannot be solved in large dimensions in an acceptable time. Therefore, to do this, we developed a meta-heuristic algorithm. The details are described at below.

## 5-2-Designing a non-dominated sorting genetic algorithm (NSGAII) for the proposed problem

This section is going to give details on how to implement the genetic algorithm, the operators used in the algorithm and how to generate the answer. To consider the answer of the problem in the form of a chromosome, it is necessary for this chromosome to be able to show the relevant decisions for the SC's echelons, separately. Location of SC facilities and volume of distribution among different echelons are among these decisions. For this purpose, the chromosome in question consists of a two-part approach. The first part indicates the locations and the second part specifies the volume of distribution of goods. The first part contains the numbers between 0 and 1. If the value of any cell is more than 0.5, it means "establishment"; otherwise, there is no establishment. The second part includes values between 0 and 1, showing the percentage of products sent from one origin to a specific destination. It is worthy to mention that the second part is interpreted according to the outcome of the first part. In other words, facilities are located based on the first part, and then in the second section, the percentage of distribution of goods is determined only for the located facility. This structure is repeated for all echelons of the SC.

Upon generation of the initial population, their fitting function is calculated. We considered the objective functions of the problem as the fitting function. After calculating the fitting function, the answers are categorized such that a number of points out of the whole set of points are considered none dominated as compared to other points. By this, several levels or fronts can be formed that, depending on the need, some of these levels are selected for the next steps, and the rest are removed. Then, to generate the next generation, cross-over and mutation operators are used. The single-point cross-over approach is employed in the cross-over operator; first two parents are selected, and then based on the chromosome formed, cross-over occur from a point and the two parts of this chromosome are replaced between the two parents. This way, two new children are generated. Then the feasibility of these two answers will be evaluated. If these two answers are possible, they will go to the next step as two new answers; otherwise, first, the chromosome is corrected and then the two answers will be transferred to the next step. For the mutation operator, a replacement between the two genes is used. First, one parent is selected randomly, and then one line of this chromosome is replaced as a gene to another line.

## 5-3-Validation of the proposed algorithm

In order to adjust the NSGAII algorithm parameters, different values have been considered for each parameter (table 4).

**Table 4.** Values of NSGAII algorithm parameters

| Parameter | Definition | Values | | |
|---|---|---|---|---|
| Npop | Number of early population | 50 | 80 | 100 |
| Max_iteration | Number of generations (iterations) | 100 | 200 | 300 |
| Cross_rate | Rate of cross-over operator | 0.5 | 0.7 | 0.9 |
| Mut_rate | Rate of mutation operator | 0.5 | 0.3 | 0.1 |

Then, using the trial and error approach based on the objective function's values, the best value for each algorithm parameter is obtained, as reported in table 5.

**Table 5.** Optimal values of NSGAII algorithm parameters

| Parameter | Best value |
|---|---|
| Npop | 100 |
| Max_iteration | 200 |
| Cross_rate | 0.7 |
| Mut_rate | 0.3 |

To verify the ***NSGAII*** algorithm's correctness, the example presented in small dimensions, which was exactly solved using GAMS software, was solved again using the proposed meta-heuristic algorithm. The results are reported in table 6.

**Table 6.** Results of solving sample problems using NSGAII

| Example | NSGAII algorithm | | | | |
|---|---|---|---|---|---|
| | Objective function 1 | Objective function 2 | Goal 1 | Goal 2 | Time (sec) |
| 1 | 236247 | 2886 | 236247 | 18086 | 1.15 |
| 2 | 238377 | 6491 | 237404 | 25418 | 2.03 |
| 3 | 356531 | 15230 | 356531 | 43446 | 4.49 |
| 4 | 443894 | 26072 | 441649 | 47612 | 8.33 |
| 5 | 590737 | 39635 | 590551 | 56764 | 13.41 |
| 6 | 694648 | 58223 | 694608 | 67884 | 20.23 |

As shown in tables 3 and 6, the proposed *NSGAII* algorithm has the ability to achieve a similar answer to that of the exact solution in solving small-scale problems, and there is only a very small difference in the last two examples with the answer obtained from the exact solution.

**Table 7.** Objective functions difference ratio by two methods

| Example | Difference (%) |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 0 |
| 4 | 0 |
| 5 | 0.01 |
| 6 | 0.03 |

The value of the difference in table 7 is obtained from the sum of the ratio of difference between the objective functions of the two approaches to the objective function value of the exact GAMS solution.

## 5-4-Solving sample problems in large dimensions

Having evaluated the accuracy of the proposed NSGAII algorithm, and in order to study its performance, several problems in larger dimensions have been designed and solved using the same algorithm. The number of each of the centers is reported in table 8.

**Table 8.** Value of SCN sets

| Parameter | Value |
|---|---|
| No. of suppliers | 10-20 |
| No. of production centers | 12-20 |
| No. of distribution centers | 15-25 |
| No. of customers | 50-100 |
| No. of collection centers | 10-15 |
| No. of recovery centers | 8-15 |
| No. of disposal centers | 8-15 |
| No. of products | 10-15 |
| No. of raw materials | 8-15 |

The above problem has been implemented in the MATLAB software and has been solved using ***NSGAII*** algorithm. The answers with the least deviation from the ideal values obtained by solving five large-scale sample problems are given in table 9.

**Table 9.** Results obtained from solving the sample problems with the NSGAII algorithm

| Example | Objective function 1 | Objective function 2 | Solution time (s) |
|---|---|---|---|
| 1 | 848986 | 73328 | 32.11 |
| 2 | 1037279 | 91308 | 58.42 |
| 3 | 1203176 | 108624 | 80.27 |
| 4 | 1437000 | 123742 | 112.38 |
| 5 | 1651303 | 148698 | 144.49 |

As indicated in table 9, as the dimensions of the problem increase, the system reliability and its total cost increase too. The answers obtained for each problem are illustrated in figure 3.

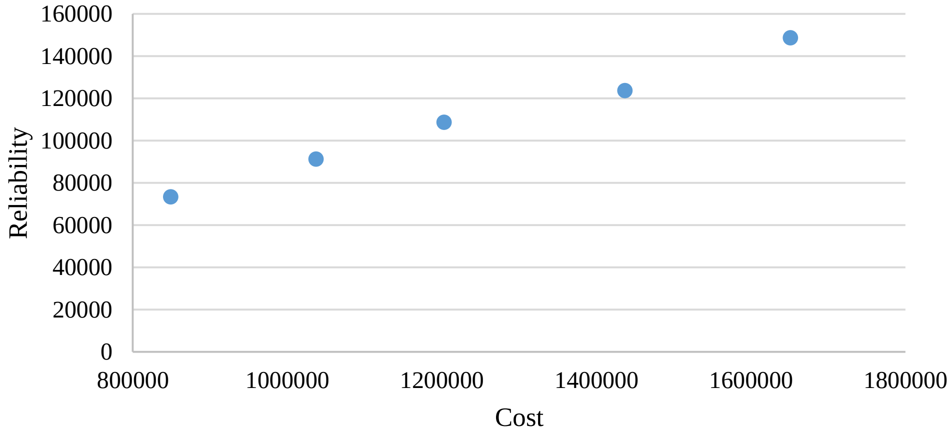


**Fig. 3.** Total cost and reliability obtained for each problem

The time process variations of solving problems based on different scales are illustrated in figure 4.

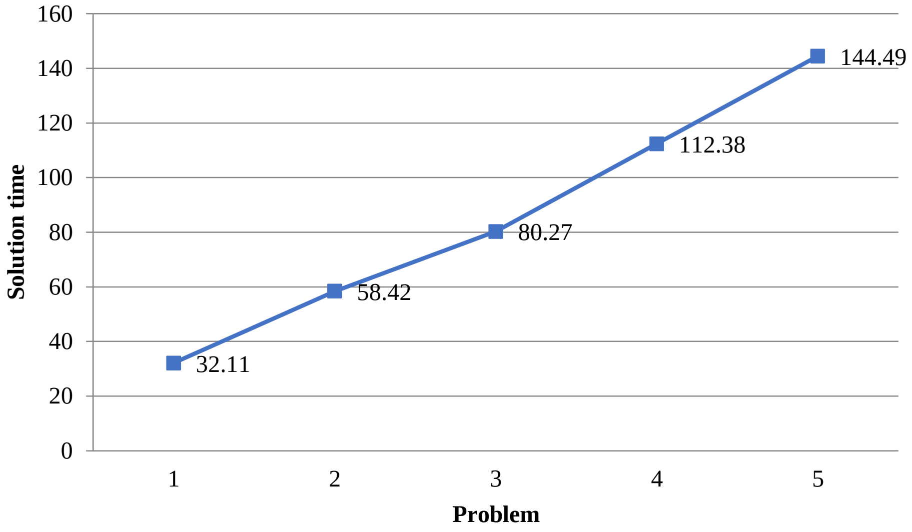


**Fig. 4.** Solution time of sample problems using proposed NSGAII algorithm

In general, the results indicate that the solution time increases as the problem size get bigger.

## 5-5-Sensitivity analysis

Here, we explain the sensitivity analysis performed on the key problem parameters, including customer demand, which may affect the flow of materials in the network, as well as the disposable and returned products' flow rate, which may affect the return flow in the reverse direction of SC, in addition to the probability of disruption. To do this, a range of changes (-20 to +20%) has been considered for the parameters (table 10).

**Table 10.** Value of objective functions via changing the value of parameters

| *Objective functions* | *Change range* | | | | |
|---|---|---|---|---|---|
| | -20% | -10% | 0 | +10% | +20% |
| The first objective function value based on change of $D_{cp}$ | 236247 | 236247 | 236247 | 239188 | 242129 |
| The second objective function value based on change of $D_{cp}$ | 2817 | 2817 | 2886 | 3174 | 3463 |
| The first objective function value based on change of $\tau$ | 236920 | 236247 | 236247 | 236247 | 236247 |
| The second objective function value based on change of $\tau$ | 2908 | 2897 | 2886 | 2875 | 2864 |
| The first objective function value based on change of $\alpha_{pc}$ | 236247 | 236247 | 236247 | 240075 | 237111 |
| The second objective function value based on change of $\alpha_{pc}$ | 2903 | 2894 | 2886 | 2874 | 2886 |
| The first objective function value based on change of $\beta_p$ | 236247 | 236247 | 236247 | 236251 | 236270 |
| The second objective function value based on change of $\beta_p$ | 2886 | 2886 | 2886 | 2886 | 2886 |

The effect of each parameter on the objective functions was investigated. As displayed in figure 5, as demand increases, the value of both objective functions increases, while decreasing it has no significant effect on the objective function. Therefore, one can conclude that increasing the amount of demand has an increasing effect on the objective functions.

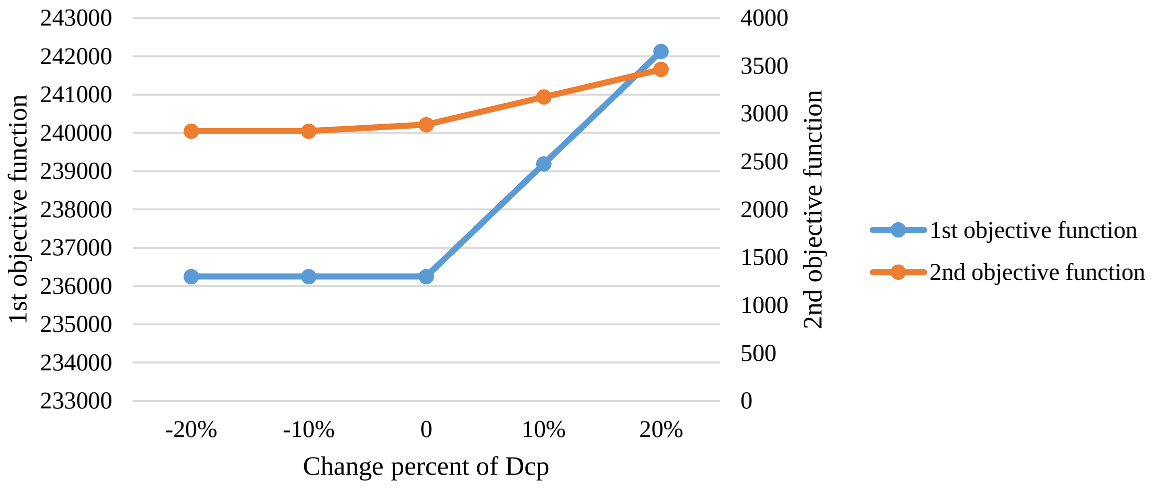


**Fig. 5.** Variations of objective functions by changing the amount of demand

Figure 6 indicates the effect of probability of disruption in the objective functions. As shown, the occurrence of a disruption imposes a cost in the system, but variation in the probability of disruption does not cause a significant change on the system cost. On the contrary, as the probability of disruption increases, the system reliability decreases significantly, appearing to follow a reasonable trend.

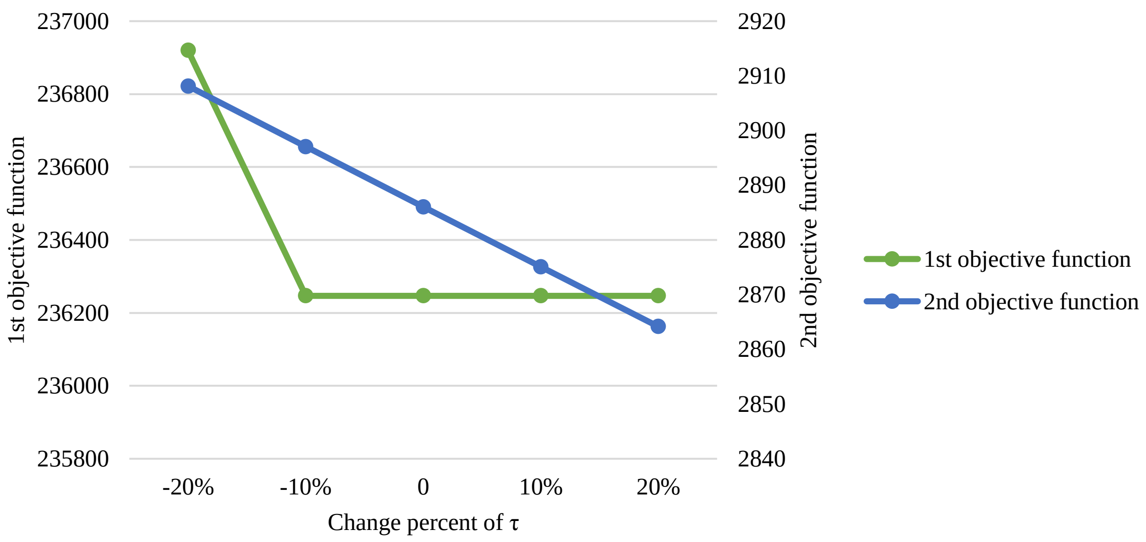


**Fig. 6.** Variations of objective functions by changing disruption probability

As stated earlier, in order to use the weighted goal programming approach, a weight is considered for each of the objective functions that the sum of them is equal to one. To do this, sensitivity analysis is performed on the weights assigned to each of the functions and its effect on the goal objective function was evaluated. As displayed in figure 7, increasing the weight or importance of the first objective function leads to decrease the cost.

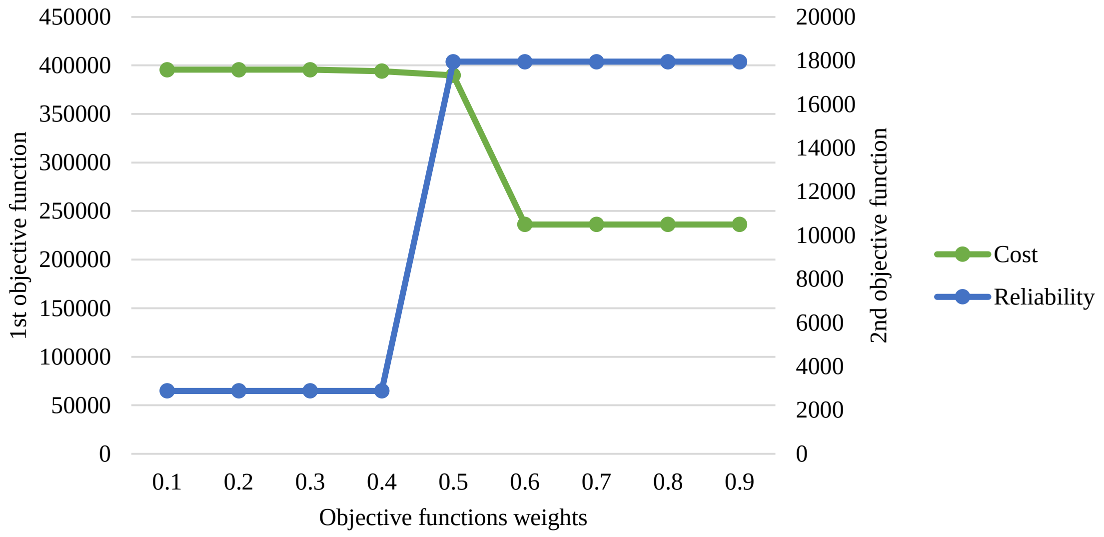


**Fig. 7.** Effect of changing the importance of objective functions on their values

On the other hand, any increase in the second objective function's importance may increase the amount of system reliability. This shows that the weight of the functions in the goal programming approach directly affects the values of objective functions. The weighted sum of differences between the objective functions obtained from their goal values is shown in figure 8.

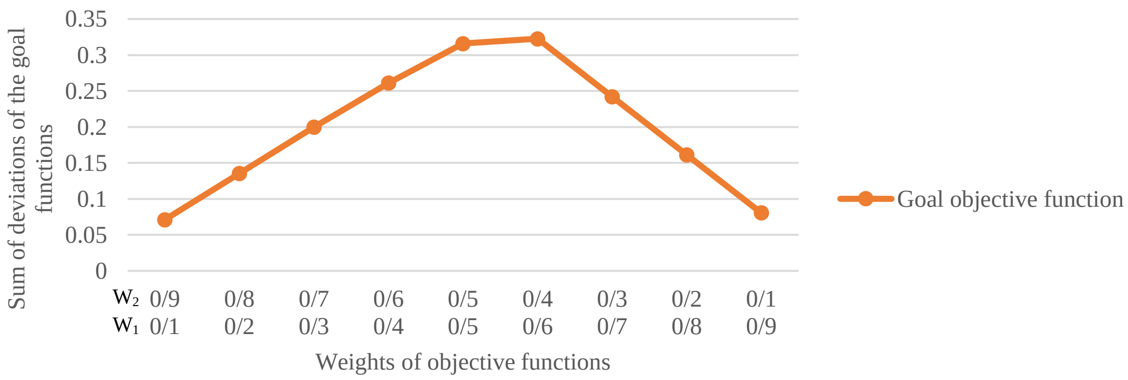


**Fig. 8.** Effect of variation in the objective functions' importance on the sum of deviations

Figure 8 (vertical axis) shows the sum of deviations of the goal functions such that the closer this value is to zero, the closer the values obtained for the objective functions are to the goal values. In addition, the horizontal axis represents the weight of each objective function, so that the first and second lines represent the weight of the second and first objective functions, respectively. As can be seen, when any of the objective functions alone enjoys a high value of importance, the sum of the deviations obtained decreases; however, when both of the objective functions have equal importance to decision-maker, the difference from the value of the goal of both functions increases, and thus, the sum of the deviations increases.

## 6-Conclusion and further research

The present study investigated a closed loop multi-echelon SC problem with the probability of disruption in the distribution center aiming to minimize the total costs of SC and maximize the system reliability. We employed a weighted goal programming method for solving the multi-objective MILP using the GAMS software and the Cplex solver. Since the model is Np-hard, the NSGA-II meta-heuristic algorithm was developed to solve it in large-scale cases. Next, its validity was examined, resulting in the generation of several large-scale problems, which were solved using the proposed algorithm. The findings revealed that the proposed algorithm results in optimal performance. Moreover, the results of sensitivity analysis on the key problem parameters, including customer demand, disruption probability, and flow rate of disposable and returned products, showed that increasing the amount of customer demand increased the value of both functions, while its decrease had no significant effect on any of the objective functions. The occurrence of disruption may also impose a cost to the system; however, its probability causes no significant change on the cost of the system. In the meantime, as the probability of disruption increases, the system reliability decreases significantly.

In this paper, only the probability of disruption in distribution centers has been considered; it is suggested that future studies consider this disruption for other centers as well. As mentioned, the input parameters of the problem were definite; hence, by bringing the model closer to real-world conditions, some parameters can be considered uncertain and various approaches such as stochastic programming (Aghighi et al., 2021), robust optimization (Alimoradi et al., 2016) and fuzzy programming (Alinezhad et al., 2021) can be used. Furthermore, more aspects of sustainability; e.g., environmental impacts minimization (Tirkolaee et al., 2021, 2022), can be studied in order to make the proposed methodology fully sustainable.

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