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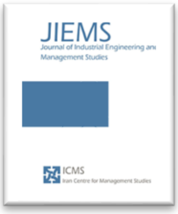

Design of a scenario-based multi-level and multi-objective mathematical model with the aim of reducing the risk of the blood supply chain in the conditions of the COVID-19 pandemic

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Abstract

Supply chain risk management is a preventive approach to risk management in the supply chain to avoid possible unexpected consequences and to manage the blood supply chain (BSC) and achieve the maximum effectiveness and efficiency of this chain, risk management of the BSC is inevitable. This research aims to propose a mathematical model to reduce the risk of the BSC in the conditions of the COVID-19 pandemic. One of the most important contributions of this research is to consider the uncertainty in the demand parameter in the conditions of the COVID-19 pandemic and to provide a robust planning model to overcome it in order to properly manage and control its risks. For this purpose, in this research a scenario-based multi-objective model is proposed with the aim of reducing the risk of the BSC in the conditions of the COVID-19 pandemic. In order to test the model, the problem is investigated in different sizes and using actual data and the results are presented, and sensitivity analysis is carried out on the changes in the parameters. Baron solver in GAMS 24.9 software is used to solve the proposed mathematical model. The proposed model determines the product sent from the blood center to the hospital, the amount of product produced in the blood center, the amount of blood collected from donors, the number of collection centers, the amount of blood stock in the blood center and hospital with the aim of reducing cost and risk and increasing reliability. In this research, a scenario-based non-linear integer multi-objective model is proposed considering the level of supply and with the aim of reducing the risk of the BSC by reducing the cost and increasing the reliability of the BSC in the conditions of the COVID-19 pandemic, which can be used for risk management of the BSC in critical conditions of blood supply, such as the COVID-19 pandemic. Finally, to measure the sensitivity of the presented model performance to the change in the parameters, the sensitivity analysis on the behavior of the model in terms of the change in the shortage cost, the number of blood collection facilities and the objective functions is presented. The sensitivity analysis on the shortage cost parameter showed that with the increase in the shortage cost, the shortage rate decreased and this leads to an increase in the total cost.

Keywords: Blood Supply Chain, COVID-19 pandemic, Risk

Paper Type: Original Research

1. Introduction

In recent years, global healthcare has aimed to improve service delivery, reduce healthcare costs, and waste of resources, while maintaining service levels, safety, and public health (Uthayakumar and Priyan, 2015). Blood management as a part of the health supply system is of a special information for humans; therefore, the collection and management of blood distribution, which is in the form of BSC management, requires careful management and planning, because any observation and interruption in the blood flow leads to human death (Duan and Liao, 2014). Given that the only source of blood is blood donation, this makes the issue of blood supply very difficult and vital. This chain is different from the supply chain of normal goods because the supply of blood is relatively irregular and uncertain and the demand for this product is also uncertain; thus, the matching of supply and demand in an efficient manner according to the demand of hospitals for blood in normal and critical conditions are complicated and require detailed and comprehensive planning (Motamedi et al., 2019) and critical conditions such as the COVID-19 pandemic have added to this complexity. The special characteristics of blood products, random

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behaviors in the areas of demand and supply, as well as the importance of blood for humans have drawn attention to the BSC for experts, scientists, and governments (Motamedi et al., 2019; Asgharizadeh et al. 2022). Zsidisin (2003) has described risk in the supply chain as "the potential probability of an incident or lack of access to opportunities with input supply, the results of which led to financial losses for the company". As a result, it can be stated that risk is the potential possibility of failure between supply chain components that may affect the flow of information, materials, and money in the supply chain network. Supply chain risk management is a proactive approach to managing risks in the supply chain to avoid possible unexpected consequences (Ritchie and Brindley, 2009). Supply chain risk and disruption is one of the stakeholders' concerns, and risk assessment is necessary due to the growing complexity of markets (Sakib et al., 2021; Daneshvar et al. 2023). Supply chain risk management is defined as the power of management teams to effectively contribute to the flexibility of the healthcare supply chain (Zamila et al., 2021; Emami et al. 2023) and the effective assessment of risks in the supply chain can lead to its improvement. Miah et al., 2013). Supply chain risk management is a new paradigm in the BSC that can be investigated to manage risks in complex and dynamic supply and demand networks (Gitimai and Bonyanusit, 2014; Babaeinesami et al. 2022). The types of risk in the BSC can be classified according to the traditional supply chain risk, including physical, financial, information, and communication flows (Cavinato, 2004; Speakman and Davis, 2004; Jutner, 2005; Faisal, 2009). To manage the BSC and achieve maximum effectiveness and efficiency of this chain, it is inevitable to manage the risk of the BSC. The outbreak of the Coronavirus (COVID-19) from Wuhan, China and its transformation into a global pandemic has put great pressure on healthcare systems across the world (Zamila et al., 2021) and even caused disturbances in the daily life of people. Countries have taken and made many measures and efforts to control the spread of the disease and manage it (Aildiz et al., 2021). However, as of April 11, 2022, the number of confirmed cases has reached 497,057,239 million and more than 6,179,104 deaths have been reported. In the meantime, Iran is not immune from this pandemic and 7,191,643 infected people and 140,616 deaths have been reported (WHO) (Jahangiri et al., 2023). Pandemic conditions have had a very negative impact on the BSC by reducing the number of donors and reducing the availability of appropriate collection facilities, thereby affecting blood transfusion services worldwide (Ratoria and Kusamb, 2020, Theo, 2009), so that in the early weeks after the COVID-19 pandemic, a 20-30% decrease in blood donation was observed, which negatively affected the entire BSC (Shokouhifar and Ranjbarimesan, 2022). In the conditions of the COVID-19 pandemic, social restrictions, suspension of public activities, school, and universities, change of work to working from home, fear, and panic among people to donate blood, and social distancing measures implemented by governments put blood donation under a lot of pressure. The lack of complete activity of mobile blood centers during a long period and the fear of donors of contracting the virus added to the cancellation of blood donation and the unwillingness to attend blood donation centers to donate blood. While it is seen in the media that many blood centers around the world are facing many problems to collect enough blood to meet the demand of the hospital and blood transfusion services are facing significant problems to maintain a safe blood supply (Jennifer et al., 2020; Hosseini et al. 2022).As a result of the COVID-19 pandemic, a large number of people are admitted to the hospital (Zamila et al., 2021), while there is a small possibility that this group of hospitalized patients will need blood transfusions due to coronavirus and that non-urgent clinical interventions are usually postponed; consequently, the demand for blood does not increase (Ratoria and Kusamb, 2020), but there are still a large number of patients who need blood transfusions to save their lives, some of the numerous uses of blood include surgeries, burn treatment, chemotherapy, thalassemia patients, hemophilia patients, and dialysis patients (Motamedi et al., 2018). While the assurance of blood supply during the COVID-19 pandemic is of great importance, the timeliness and availability of blood products due to the decrease in the number of donors (Ratoria and Kusamb, 2020) pose an important challenge in the supply chain. As a result, planning and taking action to prevent the risks of the BSC and minimize the destructive effects of these risks can lead to the improvement of the performance of the BSC. To design an efficient supply chain network, it is very important to have an optimal blood collection and distribution network (Zahiri et al., 2015), and the efficiency of BSCs can be significantly improved through mathematical programming such as operations research.

The study of the research literature suggests that no study has been conducted on mathematical modeling for managing the risks of the BSC in the conditions of the COVID-19 pandemic. Subsequently, in order to supply blood to the demand points and reduce risk in the BSC in the conditions of the COVID-19 pandemic, in this article, a scenario-based multi-level and multi-objective mathematical of the BSC is proposed, which includes blood supply, processing, and distribution level at demand points. Therefore, main research question (RQ) is as follow:

(RQ) What is the optimal robust risk management model of the blood supply chain in the conditions of the corona pandemic?

Also, main unique contribution of current study is as follow:

Considering the uncertainty in the demand parameter in the conditions of the COVID-19 pandemic and to provide a robust planning model to overcome it in order to properly manage and control its risks.

In Figure 1, a big picture of the implementation stages of the research is shown. Based on that, first, a deep study in the research literature is done to identify the weak points of the existing models. Then, problem modeling is done based on the development of objective functions and constraints. Then, the established model is estimated. Finally, the obtained results are analyzed.

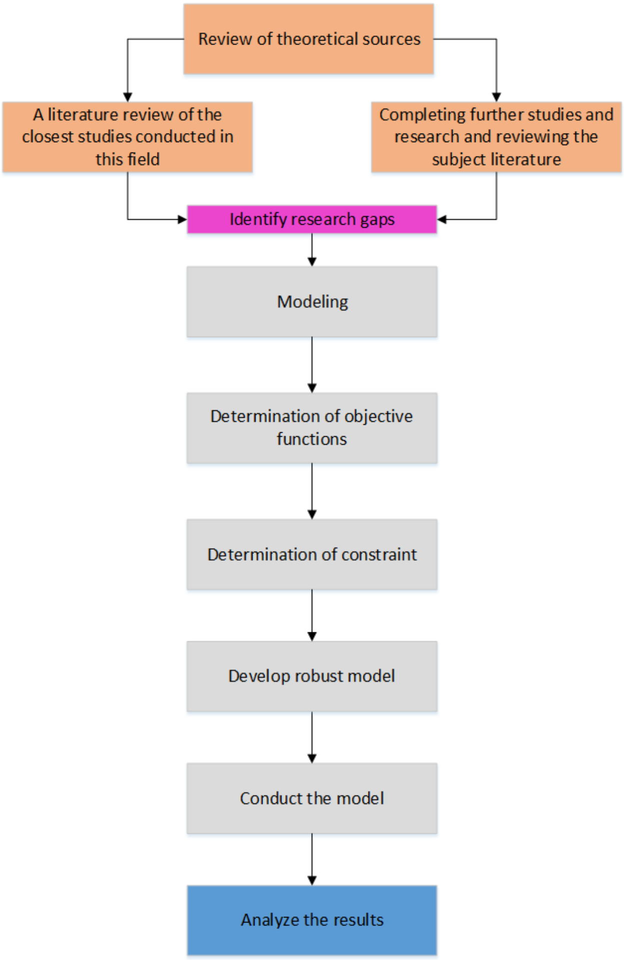

Figure 1. Research big picture

The rest of the paper is organized as indicated. In the second section, a literature review of previous research is presented. In the third section, mathematical modeling is developed. All parameters and variables, constraints and objective functions are described. In the fourth section, the practical results of the proposed model are presented. Finally, in the fifth section, a general conclusion is presented along with future suggestions.

2. Literature review

In this section, the literature related to the BSC is briefly reviewed. BSC management research was initiated in 1964 by van Zyl (1964). Maashisani et al. (2022) presented a model for optimizing the blood demand of hospitals, reducing the shortage and waste of blood and reducing the remaining stock in hospitals, as well as minimizing the cycle of blood transfusion to medical centers in the BSC. The presented model is bi-objective, three-level and multi-period, taking into account the uncertainty of demand in hospitals in a fuzzy form. Shokouhifar and Ranjbarimesan (2022) presented a multivariate time-series deep learning model based on short-term memory for forecasting blood donation and demand, which is able to manage uncertainties during the COVID pandemic to achieve resilient blood inventory management. Corinna Cagliano et al. (2022) extended an existing healthcare supply chain risk management framework already applied to the blood transfusion process to address multiple BSC echelons and identify the cause-and-effect relationships among the adverse events that might occur. he first application of the proposed approach to a blood bank and a hospital ward revealed its effectiveness in identifying the BSC activities most subjected to risk. Ghasemi et al. (2022), presented a bi-level blood supply chain network under uncertainty during the COVID-19 pandemic outbreak using a game theory technique. A new two-phase bi-level mixed-integer linear programming model was developed in which the total costs were minimized and the utility of donors was maximized. Sibevei et al. (2022) presented a probabilistic robust two-stage scenario-based model considering two disruptions in the multi-level supply chain of blood and considering their effects. The achieved results proved that adopting strategies such as redundancy, flexibility, and expanding social responsibility makes it is possible to make the blood supply chain resilient and reduce the shortage when faced with disruptions. Shakouhifar et al. (2021)

presented an inventory management model in the BSC considering fuzzy supply/demand uncertainties with the aim of minimizing shortage and wastage simultaneously across the BSC. The results demonstrated that lateral transshipment between different demand nodes has a major impact on load balancing leads to simultaneously reduce both shortage and wastage costs. Arani et al. (2021), designed a four-level collateral blood supply chain network under uncertainty, including the levels of donors, blood collection centers, blood centers, and hospitals. The three objectives of the model referring to the three underlying concepts of sustainability, additionally, to cope with uncertainties and multi objectiveness, a scenario-based optimization approach and revised multi-choice goal programming technique were employed, respectively. The results confirmed that the lateral supply improved the performance indicators. Soltani et al. (2021) presented the green blood supply chain network in disasters based on the hub location approach and considering intercity transportation with the aim of minimizing the total cost and the harmful environmental effects of transportation between facilities and waste in the network. Ghahremani-Nahr et al. (2021) presented a BSC network to reduce the cost of the entire supply chain network under demand and transportation costs under conditions of uncertainty. The network levels considered for modeling included blood donation clusters, permanent and temporary blood transfusion centers, main laboratory centers, and blood supply points. Other goals included determining the optimal number and location of potential facilities, optimal allocation of the flow of goods between the selected facilities and determining the most suitable transport route to distribute the goods to customer areas in uncertainty conditions. Chandra Pandey et al. (2021) investigated the impact of SARS-CoV-2 pandemic on blood collection and demand as well as the impact of disaster planning in maintaining an adequate inventory. The results showed a drastic fall in the red cell inventory as compared to pre-COVID-19 period due to disproportionate decrease in blood collection and demand. The buffer stock fell gradually over a period of three weeks with cancellation of planned blood donation drives. A buffer stock equivalent to 2-week inventory led to adequate inventory in the initial lockdown periods. Similar fall was observed in the platelet inventory with reduction in the blood collection but almost a proportionate reduction in the platelet demand led to adequate inventory. No increase in wastage was observed for both red cells and platelets during this period. Ghatre Samani and Hosseini-Motlagh (2021) proposed a disaster relief blood supply chain network with multiple echelons and multiple products. It incorporates the blood donors' behavior and preference for the selection of facilities where the blood donation takes place, estimating the quantity of the injured people under each disaster scenario, the inherent uncertainty in input parameters, and the remaining capacity for satisfying the demand affected by the disruption in blood facilities. The obtained results demonstrate that the related managers should be aware of blood donors' behavior, injured people in disaster, and the effect of disruption in the blood supply chain network design. Moreover, when it comes to the uncertainty of parameters, the obtained results from the robust model overcome those of deterministic one. Shirazi et al. (2021) designed a four-echelon supply chain to locate the blood collection centers, to find out how the collection centers are allocated to the temporary or permanent plasma-processing facilities, how the temporary facilities are allocated to the permanent ones, along with determining the allocation of the temporary and permanent facilities to hospitals. The achieved results indicated that as the plasma demand increases, the amount of total system costs and flow time rise as well. Farrokhizadeh et al. (2021) proposed a multi-period bi-objective mixed-integer mathematical model under a multiple scenario, aiming to minimize the unsatisfied blood demand as well as the total cost of the network. The results showed that opening new blood centers near the high-demand sub-districts for faster testing and supply, increasing the hospitals' capacities, and usage of drones and helicopters for blood distribution can be considered as effective managerial insights. Erlansari et al. (2021) proposed a mathematical model to solve the problems of the blood supply chain in the COVID-19 pandemic with the aim of providing a solution to the problems of blood distribution during the COVID-19 pandemic. The Backpropagation algorithm was used to improve the possibility of discovering available and potential donors. Furthermore, the distances, age, and length of donation were measured to obtain the right person to donate blood when it needed. Seyfi-Shishavan et al. (2021) presented a new fuzzy multi-period mathematical model using trapezoidal fuzzy numbers with the aim of minimizing the total cost of the blood supply network and total blood shortage under uncertainty and crisis. The proposed model was formulated by fuzzy objective function and fuzzy variables. Darvish Motevali and Motamedi (2020) calculated the efficiency of multi-stage and sequential supply networks by presenting a mathematical model. In addition to the sequential structure, this type of network has specific and common components that overshadow the system's performance over time. Motamedi et al. (2019) presented a multi-level multi-objective mathematical programming model with the objectives of reducing cost and increasing reliability in the blood supply chain. The results showed that the reliability of the supply chain can be increased by increasing the number of collection centers and the amount of blood sent from these centers to blood centers and blood inventory management in these centers. Osorio et al. (2018) conducted a study with the aim of minimizing the total cost of blood collection and minimizing the number of blood donors, considering the uncertainty of demand. Clay et al. (2018) presented a model regarding blood inventory fluctuations due to random supply, random demand, spoilage, and blood distribution and issuance policies in the blood supply chain. Cheraghi et al. (2017) presented a robust model for designing a blood collection and distribution system under conditions of demand uncertainty with the aim of minimizing the total cost of the network, where the amount of demand was considered as the only uncertain parameter. Ensafian and Yaghoubi (2017) proposed a robust optimization model for procurement, production, and distribution in the platelet supply chain with the aim of minimizing the costs of procurement, start-up and variable production, inventory maintenance in blood centers and hospitals, delivery from blood centers to hospitals, wastage in centers and hospitals, and the shortage cost in hospitals with uncertain demand parameters and uncertainty. Yousefi Nejad Attari et al. (2017) presented a multi-choice goal programming model to reduce the wastage and shortage of blood products in hospitals in conditions of demand uncertainty. Ramezanian and Behboodi (2017) designed a blood supply chain network under uncertainty in supply and demand with regard to social aspects. Ghatreh Samani et al. (2017) presented a model for an integrated blood supply chain for disaster relief with vague parameters mixed with uncertainty, taking into account multi-product characteristics and perishability of blood products. Ahmadi and Najafi (2017) conducted research on the management of blood inventory in the hospital considering the supply and demand uncertainty and the possibility of blood transfusion. Moslemi and Mirzazadeh (2017) evaluated the performance to control uncertainty and evaluate the reliability of four stages of the blood supply chain. Azezan et al. (2017) presented a model for the collection and distribution of blood donation based on vehicle routing problems with the aim of minimizing the total cost of routing and maximizing the total amount of blood that need to be transported to blood transfusion centers. Mouatassim et al. (2016) presented a model based on hybrid game theory for logistics optimization with a case study in the blood supply chain, which minimizes the costs of each coalition according to the cost of transportation, the cost of producing unused blood bags, and also the cost of not fulfilling requests. Zahiri et al. (2015) conducted a model related to blood collection management with a robust probabilistic planning approach and the aim of reducing the total cost assuming the uncertainty of the main parameters and the uncertainty of the donation and demand amounts. By reviewing the research literature, it was observed that most of the available studies in the field of mathematical modeling of the blood supply chain are focused on the disruptions affecting the blood supply chain caused by natural crises such as earthquakes, and most of these crises face disruption and uncertainty in the level of demand. The outbreak of the COVID-19 pandemic, like all human activities affected by this pandemic, the blood supply chain was not spared from this crisis, and blood transfusion services have faced significant problems to maintain a safe source of blood. The COVID-19 pandemic has affected the blood supply by reducing blood donation and reducing the availability of suitable collection facilities. As a result, unlike all previous crises that affected the level of demand, this time the level of blood supply was affected, which is less evident in the research literature. It was addressed and it is one of the innovations of the proposed model. On the other hand, the risk and uncertainty in the supply chain of blood transfusion has been given less attention in past studies, and this research aims to provide a model that can model and optimize the objective of the model by considering the risks of blood. The supply chain is facing it in the COVID-19 pandemic. In addition, in previous studies, the supply chain of blood transfusion is generally not seen as multi-level, and in most of the proposed models, the reliability of blood transfusion facilities is either not considered or it is addressed in the form of chains without levels. By examining the mathematical models in the supply chain, it was observed that the modeling approach was carried out in order to reduce the cost, and the efficiency and optimal use of resources and facilities were given less attention. In the proposed robust model, blood efficiency was given less attention. On the other hand, most of the studies in this field have proposed integer linear programming models, which make the problem-solving space smaller and the results obtained are far from reality, and more efficient algorithms have not been provided. Due to the complexity in solving the model, which also significantly reduces the efficiency of the proposed model, it is widely used, which is considered in this research by presenting a robust hybrid nonlinear mathematical model.Given the aforementioned research gaps, this paper presents innovation as follows. As the above literature review shows, most of the existing papers ignored the risk in the supply chain of blood transfusion, and few papers can be found that have paid attention to the risk and reliability of the BSC, and in these few researches Mathematical modeling and research methods have not been used in the operation. Also, in most studies, on the basis that access to blood supply is often difficult in critical situations due to a sudden increase in demand (Motamedi et al., 2020), the level of demand has been considered in modeling, while in the conditions of the COVID-19 pandemic, the crisis was created due to the decrease in the level of supply, which has not been taken into account in previous studies. Due to the conditions of the COVID-19 pandemic, this disease has more affected the level of supply in the BSC and has been considered in the modeling of this research. In this research, a multi-objective model is proposed with the aim of reducing the risk of the BSC in the conditions of the COVID-19 pandemic. Finally, it should be stated that most of the studies in this field have presented an integer linear programming model, which makes the problem-solving space smaller and the results are far from reality. In this research, an integer nonlinear programming model is used. A mixed model is presented, which brings the results closer to reality.

3. Methodology

The investigated BSC includes a four-level network of BSC including supply, collection, processing and distribution of blood (Figure 2). Blood collection facilities collect blood from donors and the collected blood is transported to blood centers for testing and preparing products needed by patients. Finally, blood centers meet the blood demand of hospitals and medical centers based on their need for blood and blood products. Now, considering the conditions of the COVID-19, the issue is how to determine the amount of blood collected from donors by the collection facilities, the amount of blood sent from the blood center to the hospital, the number of collection centers, and the amount of blood inventory in the blood center so that the cost of the entire supply chain is minimized and its reliability is maximized according to the minimization of the risk of the supply chain, which includes the risks of blood collection planning error, error of planning patient demand for blood, shortage of blood in the blood bank, inadequate level of blood inventory in the blood storage department.

Other assumptions of the model are as follows:

- The capacity of blood bank is limited in blood centers and demand points.
- The amount of blood collected from donors by mobile facilities is equal to the amount of blood sent from the collection centers to the blood center.
- Blood storage only exists in centers.
- Blood units are transferred directly from blood centers to areas of demand.
- Blood is considered as a single product in the whole chain.
- Shortage costs occur when the demand requested by hospitals and blood centers is not fully met by blood centers and collection centers.
- Wastage costs occur when the unit of blood expires and spoils in blood centers and hospitals.
- Blood transfer is performed according to the Austrian standard. Blood bags do not get open in any way until consumption. As a result, there is no contamination and transmission of the virus to the blood at different levels of the blood supply chain.
- Blood sampling is done only from healthy people.
- In the BSC, the wastage of blood units and products is a global problem, which varies from 0 to 6% in different countries, and reaching a wastage of less than 1% is considered an indicator of quality improvement, and this amount in Iran was estimated between 2.5 and 2.9 percent (Omidkhoda et al., 2018).
- Reliability for blood transport and reliability of blood collection equipment were assumed to be 80 and 85%, respectively. Also, the reliability of meeting the blood demand in the blood center was considered 85%, and it is assumed that the reliability of other levels of the supply chain is 100% (Motamedi et al., 2019).

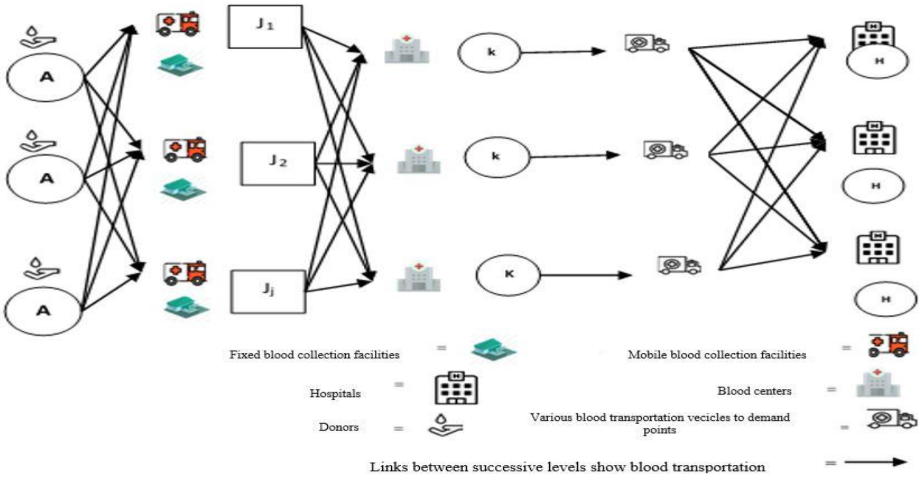

Figure 2. Blood supply chain

Indices and sets

M = set of permanent blood collection facilities $m \in M$

N = set of temporary blood collection facilities $n \in N$

K = set of blood centers $k \in K$

H = set of hospitals $h \in H$

T = time period $t \in T$

S = possible scenario $s \in S$

Parameters

Cbm_{mt} = cost of collecting each unit of blood from donors by permanent collection facility m in period t.

Cbn_{nt} = cost of collecting each unit of blood from donors by temporary collection facility n in period t.

CVm_{mkt} = cost of transporting each unit of blood from permanent collection facility m to blood center k in period t.

CVn_{nkt} = cost of transporting each unit of blood from temporary collection facility n to blood center k in period t.

CV_{kht} = cost of transporting each unit of blood from blood center k to hospital h in period t.

CH'_{ht} = average cost of maintaining each unit of blood in hospital h in period t.

CH''_{kt} = average cost of maintaining each unit of blood in blood center k in period t.

CS_{kt}= shortage cost of each unit of blood in blood center k in period t.

CW'_{k} = wastage cost of each unit of blood in blood center k in period t.

$\bar{\alpha}_1$ = average confidence regarding the conditions and safety of blood transportation in terms of temperature. etc. from permanent collection point m and temporary n to blood center k

$\bar{\alpha}_2$ = average confidence regarding the operation of laboratory equipment in collection centers

$\bar{\alpha}3_{kt}$ = average confidence regarding the fulfillment of blood demand in blood center k from permanent and temporary collection centers in period t.

$\bar{\delta}_j^1$ = average percentage of non-standard packaging of blood in permanent and temporary blood collection sites.

Db_{mkts} = demand in blood center k from permanent collection centers m in period t under scenario s.

Db'_{nkts} = demand in blood center k from temporary collection centers n in period t under scenario s.

AD_{hts} = actual demand for blood in hospital h in period t under scenario s.

D_{khts} = demand for blood units from blood center k by hospital h in period t under scenario s.

μ_{kt} = maximum capacity of blood center k in period t.

δ_m = maximum capacity of permanent collection facility m.

γ_n = maximum capacity of temporary collection facility n.

τ_{ht} = maximum blood storage capacity in hospital h in period t.

pro_s = probability of occurrence of scenario s.

Decision variables

Xbm_{mt}^{s} = amount of blood collected from donors by permanent collection facility m in period t under scenario s.

Xbn_{nt}^{s} = amount of blood collected from donors by temporary collection facility n in period t under scenario s.

Pb_{mkt}^{s} = amount of blood sent from permanent collection centers m to blood center k in period t under scenario s.

Tb_{nkt}^{s} = amount of blood sent from temporary collection centers n to blood center k in period t under scenario s.

Q_{kht}^{s} = amount of blood sent from blood center k to hospital h in period t under scenario s.

${N'_{mt}}^{s}$ = number of permanent blood collection facilities in period t under scenario s.

${N''_{nt}}^{s}$ = number of temporary blood collection facilities in period t under scenario s.

${IN'_{kt}}^{s}$ = amount of blood inventory in blood center k in period t under scenario s.

${IN''_{ht}}^{s}$ = amount of blood inventory in hospital h in period t under scenario s.

${De'}_{kt}^{s}$= amount of blood shortage in blood center k in period t under scenario s.

${WB'_{kt}}^{s}$ = amount of blood wastage in blood center k in period t under scenario s.

φ_{kmnt}^{s} = amount of non-fulfillment of the blood supply required by the blood center by donors from blood collection facilities in period t under scenario s.

$$\mathrm{MinZ1} = \sum_s pro_s \Big(\big(\sum_m \sum_t^T Cbm_{mt} \times Xbm_{mt}^{s}\big) + \big(\sum_n \sum_t^T Cbn_{nt} \times Xbn_{nt}^{s}\big) + \big(\sum_m^M \sum_k^K \sum_t^T Pb_{mkt}^{s} \times CVm_{mkt}\big) + \big(\sum_n^N \sum_k^K \sum_t^T Tb_{nkt}^{s} \times CVn_{nkt}\big) + \big(\sum_k^K \sum_t^T {IN'_{kt}}^{s} \times CH''_{kt}\big) + \big(\sum_h^H \sum_t^T {IN''_{ht}}^{s} \times CH'_{ht}\big) + \big(\sum_k^K \sum_h^H \sum_t^T Q_{kht}^{s} \times CV_{kht}\big) + \big(\sum_k^K \sum_t^T {De'}_{kt}^{s} \times CS_{kt}^{K}\big) + \sum_m^M \bar{\delta}_m^1 \big(\sum_t^T Cbm_{mt} \times Xbm_{mt}^{s}\big) + \sum_n^N \bar{\delta}_n^1 \big(\sum_t^T Cbn_{nt} \times Xbn_{nt}^{s}\big) + \big(\sum_k^K \sum_t^T {WB'_{kt}}^{s} \times CW'_{kt}\big)\Big) \tag{1}$$

$$MaxZ2 = \sum_s pro_s \Big(\Big(\bar{\alpha}_1 \times \big(\sum_m^M \sum_k^K \sum_t^T (Pb_{mkt}^{s} \div Db_{mkts}\big) + \sum_n^N \sum_k^K \sum_t^T (Tb_{nkt}^{s} \div Db'_{nkts})\big)\Big) \times \Big(\bar{\alpha}_2 \times \sum_t^T \big((N'_{mt} \times \delta_m \div (\sum_k^K (\sum_m^M Db_{mkts}) + (N''_{nt} \times \gamma_n \div (\sum_n^N Db'_{nkts})))\big)\Big) \times \Big(\bar{\alpha}3_{kt} \times \big(\sum_m^M \sum_k^K \sum_t^T (Pb_{mkt}^{s} \div Db_{mkts}\big) + \sum_n^N \sum_k^K \sum_t^T (Tb_{nkt}^{s} \div Db'_{nkts})\big)\Big)\Big) \tag{2}$$

St:

$$\sum_m^M Pb_{mkt}^{s} + \sum_n^N Tb_{nkt}^{s} \le \mu_{kt} \qquad \forall\ k \in K, t \in T, s \in S \tag{3}$$

$$\sum_n^N Tb_{nkt}^{s} = \sum_n^N Xbn_{nt}^{s} \qquad \forall\ n \in N, t \in T, s \in S \tag{4}$$

$$\sum_m^M Pb_{mkt}^{s} = \sum_m^M Xbm_{mt}^{s} \qquad \forall\ m \in M, t \in T, s \in S \tag{5}$$

$$\sum_m^M Xbm_{mt}^{s} \le \delta_m \qquad \forall\ m \in M, t \in T, s \in S \tag{6}$$

$$\textstyle\sum_{n}^{N} Xbn_{nt}^{s} \leq \gamma_n \qquad \forall\ n \in N, t \in T, s \in S \tag{7}$$

$$\textstyle\sum_{m}^{N} Pb_{mkt}^{s} + \sum_{n}^{N} Tb_{nkt}^{s} \geq \sum_{h}^{H} Q_{kht}^{s} \qquad \forall\, k \in K, t \in T, s \in S \tag{8}$$

$${IN''_{ht}}^{s} \leq \tau_{ht} \qquad \forall\ h \in H, t \in T, s \in S \tag{9}$$

$${IN'_{kt}}^{s} \leq \mu_{kt} \tag{10}$$

$$N''_{nt} \times \gamma_n + N''_{mt} \times \delta_m \geq \textstyle\sum_{m}^{M} Xbm_{mt}^{s} + \sum_{n}^{N} Xbn_{nt}^{s} \quad \forall m \in M, n \in N, t \in T, s \in S \tag{11}$$

$${IN''_{ht-1}}^{s} + \textstyle\sum_{k}^{K} Q_{kht}^{s} + De_{ht}^{s} = {IN''_{ht}}^{s} + AD_{hts} \qquad \forall\, h \in H, t \in T, s \in S \tag{12}$$

$${IN'_{kt-1}}^{s} + \textstyle\sum_{m}^{M} Pb_{mkt}^{s} + \sum_{n}^{N} Tb_{nkt}^{s} + De''_{kt} - \sum_{h}^{H} Q_{kht}^{s} = {IN''_{ht}}^{s} \qquad \forall\ k \in K, t \in T, s \in S \tag{13}$$

$${WB'_{kt}}^{s} = {IN'_{kt-1}}^{s} + \textstyle\sum_{m}^{M} Pb_{mkt} + \sum_{n}^{N} Tb_{nkt}^{s} - \sum_{h}^{H} D_{khts} - \sum_{h}^{H} De_{ht}^{s} \quad \forall\, k \in K, t \in T, s \in S \tag{14}$$

$$\textstyle\sum_{m}^{M} Xbm_{mt}^{s} + \sum_{n}^{N} Xbn_{nt}^{s} + \geq AD_{hts} \qquad \forall\ h \in H, t \in T, s \in S \tag{15}$$

$${IN'_{kt}}^{s} \leq M \times y_1 \tag{16}$$

$$De'^{s}_{kt} \leq M \times y_2 \tag{17}$$

$$y_1 + y_2 = 1 \tag{18}$$

$$\textstyle\sum_{m}^{M} Xbm_{mt}^{s} + \sum_{n}^{N} Xbn_{nt}^{s} \leq \sum_{m}^{M} \sum_{k}^{K} Db_{mkts} + \sum_{n}^{N} \sum_{k}^{K} Db'_{nkts} \quad \forall\, t \in T, s \in S \tag{19}$$

$$N''_{nt} \times \gamma_n + N''_{mt} \times \delta_m \leq \textstyle\sum_{m}^{M} \sum_{k}^{K} Db_{mkts} + \sum_{n}^{N} \sum_{k}^{K} Db'_{nkts} \qquad \forall\ t \in T, s \in S \tag{20}$$

$$\textstyle\sum_{m}^{M} Xbm_{mt}^{s} + \sum_{n}^{N} Xbn_{nt}^{s} + \varphi_{kmnt}^{s} + \sum_{k}^{K} {IN'_{kt-1}}^{s} - \sum_{k}^{K} {IN'_{kt}}^{s} = \sum_{n} \sum_{k}^{K} Db'_{nkts} + \sum_{m} \sum_{k}^{K} Db_{mkts} \qquad \forall\, t \in T, s \in S \tag{21}$$

$$Q_{kht}^{s}, N''_{nt}, N'_{mt}, {WB'_{kt}}^{s}, De_{ht}^{s} \in Z^{+} \tag{22}$$

$$Xbm_{mt}^{s}, Xbn_{nt}^{s}, Pb_{mkt}^{s}, Tb_{nkt}^{s}, {IN'_{kt}}^{s}, {IN''_{ht}}^{s}, \varphi_{kmnt}^{s} \geq 0 \tag{23}$$

$$z_1, z_2, y_1, y_2 \in \{0,1\} \tag{24}$$

The first objective function (1) minimizes the cost of the entire supply chain, which includes the cost of donating blood by donors, the cost of transporting blood, the cost of non-standard blood packaging, the cost of storage, the cost of donating blood, the cost of shortage, and the cost of wastage. The second objective function (2) maximizes the reliability of the BSC, including confidence in the conditions and safety of blood transportation in terms of temperature fluctuations, confidence in the operation of laboratory equipment in the blood collection center, confidence in meeting the blood demand in the blood center. Constraint (3) is the total blood input to the blood center from permanent and temporary donation centers is less than the total capacity of that blood center. Constraints (4) and (5) show equality between input and output of blood flow in permanent and temporary blood donation centers. These constraints ensure the balance of the flow in the collection facility and that all the blood received by the collection facility is transferred to the blood centers. Constraints (6) and (7) show the blood donation capacity by donors in permanent and temporary blood donation centers, which is at most equal to the blood receiving capacity in these centers. Constraint (8) guarantees that the amount of blood sent to hospitals does not exceed the amount of blood sent from the collection centers to the blood center. Constraint (9) shows the maximum storage capacity of blood units in the hospital. Constraint (10) shows the maximum capacity of the blood center for blood storage. Constraint (11) shows the maximum capacity of collection facilities for blood collection. Constraint (12) shows the balance of the inventory in the hospital. Constraint (13) shows the balance of the Constraint in the blood center. Constraint (14) determines the wastage amount of the blood center. Constraint (15) guarantees that the amount of collected blood covers the amount of demand. Constraints (16, 17, 18) guarantee that blood centers have either an inventory or a shortage in a period. Constraints (19, 20) show the amount of blood center demand. Constraint (21) indicates the control limit for the uncertainty in not meeting the blood supply required by the blood center by donors from the blood collection facility and if the value of φ_{kmnt}^{s} is equal to zero, we no longer have an unmet supply and the supply meets the demand of the blood center and otherwise we have unmet supply. Constraints (22, 23, 24) express the type of decision variables. Proposed nonlinear model can determine the optimal solution by utilizing optimization techniques. These techniques involve finding the values of the model's variables that minimize or maximize a certain objective function, subject to constraints. Proposed nonlinear model are characterized by having nonlinear relationships between the variables and the objective function or constraints. Unlike linear models, they do not follow a straight line or have a constant slope. One commonly used method for solving nonlinear optimization problems is called gradient-based optimization. This method uses the gradient, or derivative, of the objective function to iteratively update the variable values in search of the optimal solution. By following the direction of steepest descent or ascent, depending on whether it is a minimization or maximization problem, the algorithm converges towards the optimal solution. It's important to note that the effectiveness of these methods depends on the specific characteristics of the nonlinear model and the complexity of the problem. In some cases, finding the global optimal solution can be challenging, and the algorithm may converge to a local optimum instead.

4. Findings

To evaluate the performance of the proposed model, a computational problem with different dimensions is investigated and the model is tested, the results of which are presented in this section. To solve the presented mathematical model, Baron solver in 24.9 GAMS software is used on a home computer. The values of the model parameters are taken from the actual data of the papers (Davoudi Kia Kalate et al., 2013) and (Nahofti Kohneh et al., 2016). The model is solved using the above data after de-scaling the parameters and to confirm its performance on the change of the shortage cost parameters and the performance of the objective functions, a sensitivity analysis was performed, the report of which is given below. To investigate the model's solvability in different dimensions, five samples in different sizes are generated, the results of which are presented in Table 1. In Table 1, the second column shows the number of members of each sample. The members are m, n, k, h, t, and s, where m is the number of fixed blood collection facilities, n is the temporary collection facility, k is the number of blood centers, h is the number of hospitals, t is the number of periods, and s is the number of scenarios. The results show that the solution time increases with the increase in the dimensions of the problem.

Table 1. Numerical experiments

Execution number	Sample size	Optimal value of objective function	Solving time (hours)
1	(2,2,2,4,2,2)	2.567678E+9	01:30:30.249
2	(2,2,2,8,3,2)	2.745287E+9	01:34:32.125
3	(2,6,1,10,2,2)	3.672987E+9	02:12:45.095
4	(2,6,2,15,2,2)	5.767847E+9	02:62:09.235
5	(3,10,2,30,2,2)	1.15699E+10	03:04:41.063

4.1. Sensitivity analysis

In this section, we measure the performance of the proposed model in terms of changes in model parameters for dimensions (30, 2, 2, 2, 3, 7). For this purpose, in order to measure the performance sensitivity of the proposed model to the change in the parameters, in this section we will examine the behavior of the model in terms of the change in the shortage cost, the number of blood collection facilities, and the objective functions. The sensitivity analysis on the shortage cost parameter shows that as the shortage cost increases, the shortage rate decreases and this results in an increase in the total cost (Table 2), the results confirm the accuracy of the proposed model.

Table 2. Changes in the cost of blood shortage in the blood center

Experiment	Cost of blood shortage in blood center	Shortage in blood center				Values of Objective function (2)
		S 1		S 2		
		Period 1	Period 2	Period 1	Period 2	
1	0.0	1328	843	258	227	21.153
2	0.00095	1327	842	258	226	21.153
3	0.00332	1149	793	257	127	28.153
4	0.0094	1107	713	176	54	33.284
5	0.0187	1016	709	45	39	42.714
6	0.1562	872	445	23	0	60.745
7	0.3125	328	323	0	0	95.683
8	0.6250	194	87	0	0	95.699
9	1.0180	37	36	0	0	96.095
10	1.8750	37	37	0	0	95.089

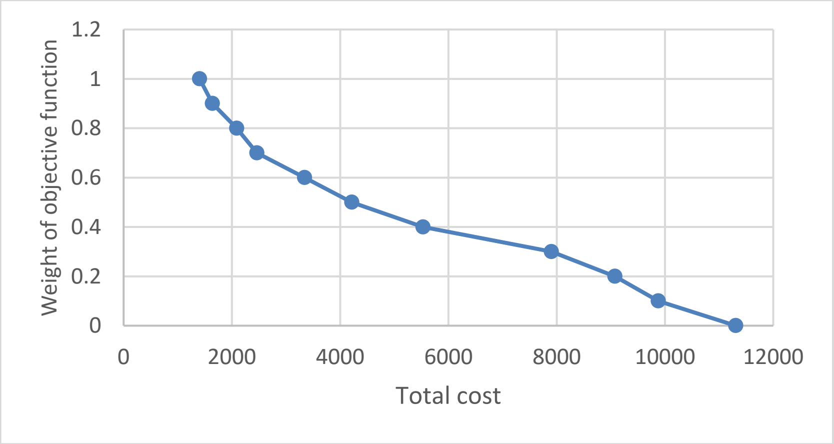

Figure 3. Minimization of total cost

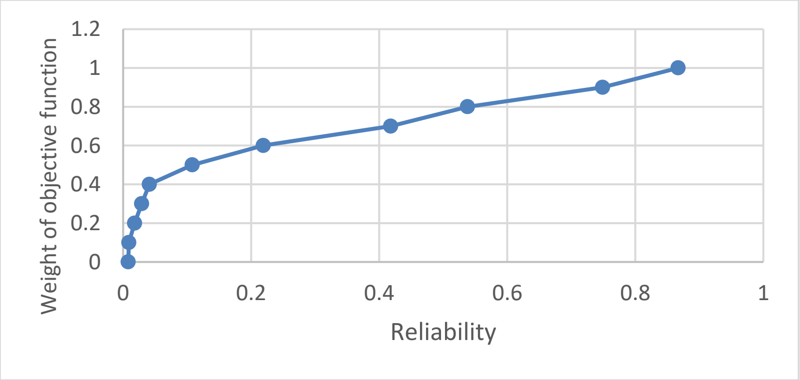

Figure 4. Maximization of reliability

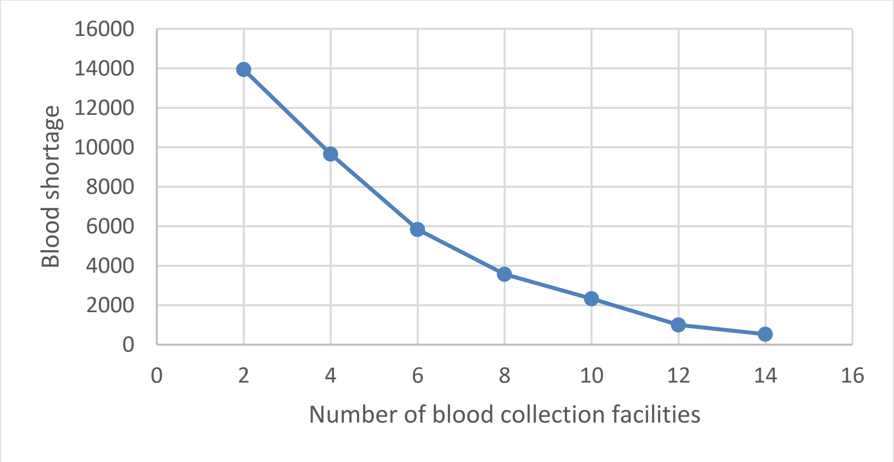

Figure 5. Shortage changes in the blood center against the number of blood collection facilities

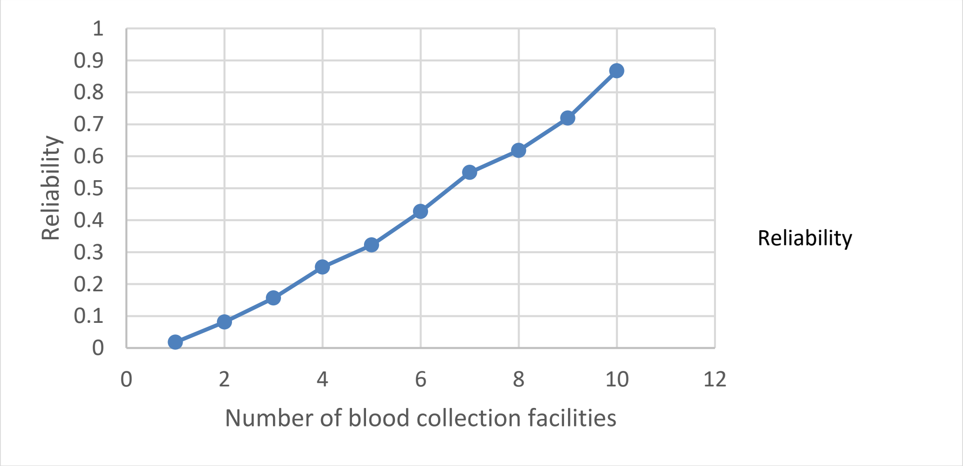

Figure 6. Reliability against the number of blood collection facilities

The proposed model is a mixed non-linear integer programming multi-objective model with the aim of reducing the BSC risk in the conditions of the COVID-19 pandemic. For this purpose, the two objective functions of the model aim to maximize the reliability and minimize the cost of the entire BSC. The weight method is used to solve the model. In order to analyze the sensitivity of the objective function, different weights were created for objective functions with a weight value (0 to 1). In order to avoid complicating the problem and taking into account the conditions of the COVID pandemic, two scenarios are considered based on the reduction of supply and the equality of supply and demand. In the first scenario, the amount of supply is reduced, which leads to blood shortage, and in the second scenario, the amount of demand is equal to the supply. Finally, after consulting with the experts of the blood transfusion organization in this BSC, the probability of the first scenario is 0.7 and the second scenario is 0.3.As can be seen in Figure 3, with the increase in the weight of the objective function for cost minimization, the objective function moves towards minimization and optimization, and also with the increase in the weight of the objective function for reliability maximization, the value of the objective function moves towards maximization and optimization (Figure 4), which indicates the accuracy of the proposed model. Figure 5 illustrates the Pareto of shortage changes in the blood center against the number of blood collection facilities and that there is an inverse relationship between the two variables and the amount of shortage decreases with the increase in the number of blood collection facilities. Also, Figure 6 demonstrates reliability changes against the number of blood collection facilities and that there is a direct relationship between the two and the reliability of the system increases with the increase in the number of blood collection facilities. As can be seen in the model, the presented model is a multi-objective model of mixed non-linear integer programming, where the two objective functions of the model are to maximize reliability and minimize the cost of the entire blood supply chain. The weight method was used to solve the model. To analyze the sensitivity of the objective function, different weights for the objective functions were created for a problem with dimensions (25, 2, 2, 2, 4, and 6) with weight value (0 to 1). Figure (7) shows the minimization of the total cost in the robust model and it can be seen that with the increase in the weight of the cost minimization objective function, the objective function moves towards minimization and optimization and its value in the weight is based on 0.1. Also, by increasing the weight in the reliability maximization objective function, the objective function value is based on 0.5 and moves towards maximization and reaches its maximum value at the weight of 1 (Figure 8), which indicates the accuracy of the performance. The presented model is robust.

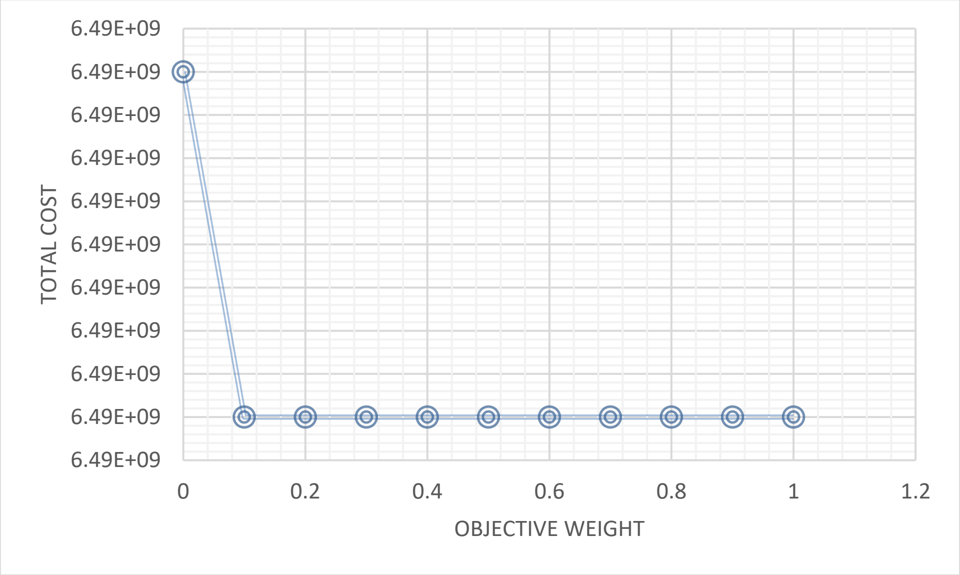

Figure 7. Minimization total cost in robust model

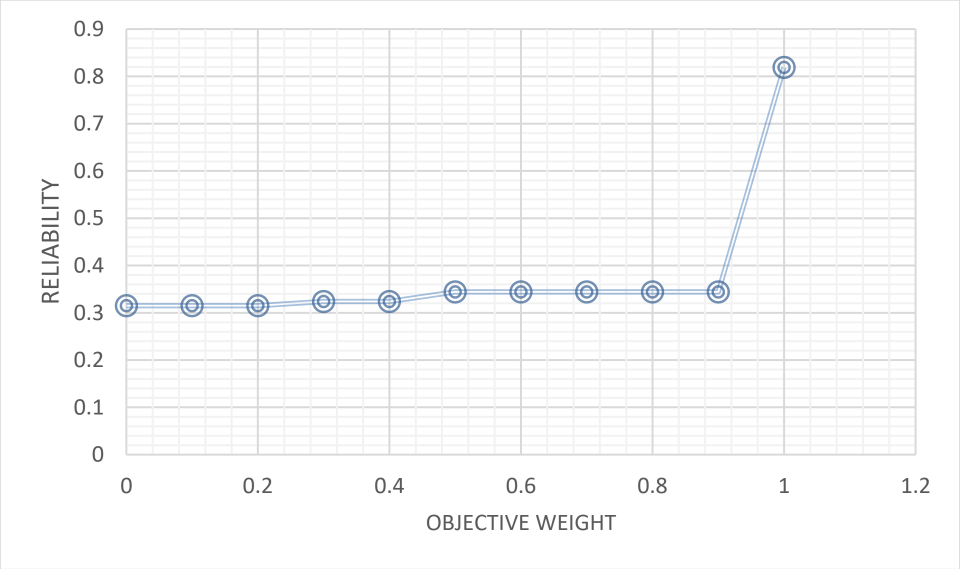

Figure 8. Maximization of reliability

5. Discussion and Conclusion

The model designed in this research determines the values of decision variables, including the amount of blood collected from donors by permanent and temporary collection facilities, the amount of blood sent from permanent and temporary collection centers to the blood center, blood sent from the blood center to hospital, the number of permanent and temporary blood collection facilities, the amount of blood inventory in each center and hospital with the aim of reducing the total cost and increasing the reliability of the BSC, and also minimizes the wastage and shortage in the blood center simultaneously. According to the researchers' search in the literature, the number of papers on BSC that have taken into account reliability modeling is very limited. Aghiani et al. (2015) presented a robust optimization model for the reliable design of the BSC network considering possible disruptions in blood collection facilities, blood transportation routes, and blood centers during a crisis with the aim of minimizing the lack of coverage of demand points and increasing reliability of BSC in crisis conditions. The research results are consistent with the research results of Aghiani et al. (2015), and in both researches, the results show a direct relationship between the number of blood collection facilities and the reliability of the supply chain. Cagliano et al. (2022) also stated that the level of blood inventory is the most affected by the COVID-19 pandemic. Zende-Del et al. (2014) also considered only the disturbance at the location in their research and the results showed the importance of the issue of reliability in the issue of location. Motamedi et al. (2019) also concluded in their research that there is a direct relationship between increasing the reliability of the BSC and the number of blood collection facilities. Clay et al. (2018) stated that a small disturbance applied to transport causes instability and fluctuation in the model. Also, the blood inventory can affect fluctuations and cause short-term fluctuations in demand without causing instability in the system, and a decrease in fluctuations leads to less shortages and less wastage due to spoilage. The results of this research also showed that by managing the blood inventory in blood centers, the shortage can be reduced to zero and the wastage can be minimized. In this research, a scenario-based bi-objective four-level non-linear mixed integer model was presented with the aim of reducing the risks of the blood supply chain by designing two objective functions in order to reduce the total cost and increase the reliability of the BSC network in the conditions of the COVID-19 pandemic. The investigated model takes into account the uncertainty regarding the conditions and safety of blood transportation in terms of temperature fluctuations, non-standard packaging of blood in the collection place and blood centers, uncertainty regarding the operation of laboratory equipment in the blood center, uncertainty regarding The blood demand in the blood center, the amount of blood sent from the blood center to the hospital, the amount of blood collected from donors by fixed and variable facilities, the number of collection centers, the amount of blood in the blood center and the hospital with the aim of reducing the total cost and increasing the reliability according to the minimization of wastage and shortage in the blood center. The costs of the supply chain include the costs of blood collection, transportation, storage, shortage, and wastage. Considering that the most important problem of the BSC is the supply of blood to the demand points and blood shortage leads to endangering human lives, in the presented model, the amount of shortage is minimized, while the amount of inventory more than the demand to prevent the shortage also leads to blood wastage and additional cost to the blood supply network, blood wastage is minimized in the presented model. It should be noted that these two problems are in conflict with each other in the real world and are considered in the presented model. Also, increasing the reliability of the system prevents disruptions in the BSC and makes the supply chain stable and achieves its goal, which is supply of the blood needed by the demand points with the minimum total cost. This issue is also taken into consideration in the model and by minimizing the cost of the BSC, it increases its reliability. The results indicate that by increasing the number of blood collection facilities, the amount of blood sent from these centers to the blood centers can be increased, which reduces risks and increases the reliability of the BSC and responsiveness to demand. Also, with inventory management, supply chain risk can be managed and reduced. The proposed model can be developed in different ways. As a suggestion for future research, given that in the research model, blood is considered as a single product in the entire supply chain, different products derived from blood can be considered for the development of the model. Also, with the development of a robust model, the uncertainty in supply and demand can be considered in the model and a model more appropriate to the real conditions can be provided.

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