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Research Article

A Multiobjective Model for a Multilevel Blood Supply Chain to Improve the Attractiveness of Blood Centers during the COVID-19 Pandemic

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Failure to control crisis conditions leads to irreparable damage to many supply chains around the world, including blood supply chains (BSCs) as critical networks in the health system. Consequently, it significantly reduces the supply of blood and its products, as vital materials, and exerts detrimental effects on the activities of blood organizations and facilities as well as the health of individuals in society. In the present study, the proposed model seeks to simultaneously minimize the operating costs and the shortage of blood products with the aim of improving the attractiveness of blood centers during the COVID-19 pandemic. Accordingly, by optimizing the overall cost and the attractiveness of blood donation centers, an attractive efficient environment is provided. It can help to remove barriers to blood donation and improve blood health. To this end, the model takes certain strategies into account for the proper establishment of new local blood collection centers (BCCs) and mobile BCCs. It also arranges suitable transportation vehicles for the efficient transfer of blood products to the provincial centers of the candidate country and sets various incentive policies for blood donation. In order to minimize the costs of the entire supply chain network and maximize the attractiveness of the BCCs, a two-objective mathematical model is developed. It produces Pareto solutions using the ε-constraint method. Finally, the efficiency of the proposed approach and the sensitivity of the corresponding parameters are analyzed through a practical case study. The obtained results represent that a growth in the attractiveness of blood centers induces a raise in the number of donors, and, consequently, the amount of the donated blood grows. This depends on more investment at all levels of the supply chain, including collection, production, storage, and transportation. Moreover, the performance and attractiveness of a BSC can be enhanced significantly if the number of collection centers and the amount of blood sent from the receiving centers to the demand nodes are increased.

1. Introduction

Blood and its products are one of the vital strategic items for all nations and governments in the world. Blood transfusion is required due to various accidents and incidents such as car accidents, burns, and surgeries. Women in childbirth and premature babies need blood too. There is still no substitute for blood; only the blood donated by human beings can save the lives of other human beings. Lack of suitable substitutes for blood and its products, limited storage time, and the constant need for blood and its products have made blood donation particularly important.

BSC management is a challenging task in humanitarian logistics. This is related to the flow of blood products from donors to patients. A BSC includes donors, fixed and mobile blood collection facilities, donation centers, and demand points. Blood is usually in demand in hospitals, clinics, and relief centers. The flow of blood products in the chain occurs through six processes including collection, testing, production, maintenance, distribution, and transfer of blood. In this regard, it is of importance to reduce organizational costs, improve the level of service, and guarantee the satisfaction of most of the injured [1, 2].

COVID-19 is a crisis that started in late 2019 and proceeded to affect 231 countries. Until February 2023, it affected more than 677,534,551 people and took about 6,782,103 lives [3]. Its incidence has already reached one thousand people per hour [4, 5].

The conditions caused by the COVID-19 pandemic have posed obstacles to the storage of blood and its products worldwide. This problem has arisen in two ways. On the one hand, the large number of patients with the coronary artery disease has increased the consumption of blood products in hospitals. On the other hand, the reduction of traffic in the society as a result of quarantine has significantly reduced the number of blood donors. These two factors have joined hands to postpone many unnecessary surgeries and clinical treatments.

To et al. [6] found that less than 5% of eligible Americans donate blood. It has declined significantly throughout the COVID-19 pandemic. In June 2020, the US Red Cross reported that, in 29% of US blood centers, the blood supply is enough for less than a day. Statistics also show that blood donation has decreased by 86,000 units since March 2020, and 2,700 blood donation appointments have been canceled.

Yahia [7] released their eight-month experience (from August 2019 to April 2020) in blood supply and blood demand at King Abdullah Hospital, Bisha, Saudi Arabia. They pointed to a meaningful 39.5% drop in the blood supply at blood bank-based collections and a 21.7% drop in the blood demand. However, as noted, this decrease in demand was due to the postponement of surgeries and the lack of response to the needs of patients with lower priority. The current imbalance in various blood banks worldwide is more due to the reduced supply (reduced blood donation) than to the increased demand (more patient needs). Under normal circumstances, keeping an inventory of blood products in a center meets the needs of the patients there for one to two weeks. This rate drops sharply during the learning period and sometimes reaches an emergency, which will lead to the fragility of blood banks and irreparable consequences.

Wang et al. [8] declared a similar study at the first hospital affiliated to Zhejiang University School of Medicine, Hangzhou, China. They found that blood donors were mainly concerned about catching the coronavirus when donating blood.

According to a report by the World Health Organization, there is no evidence of coronavirus transmission or other respiratory viruses transmitted through blood transfusions anywhere in the world [9]. Adopting educational policies to inform individuals properly will have a meaningful impact on improving the current conditions and increasing redonation rates. Meanwhile, the role of blood facilities and the corresponding managers in making coordination with the new changes and providing a safe environment for donors is undeniable. The main points that should be considered to improve donor confidence and, thus, increase blood supply are adherence to health protocols by blood-related organizations and facilities, use of personal protective equipment such as masks and shields by both donors and staff members, regular and frequent cleaning and disinfection of the surfaces with the possibility of contamination, appropriate social distance, regular checking of COVID-19 symptoms in donors and staff members, and communication with volunteers to make sure about their health before they go to a blood donation center.

Although the virus has spread recently, the number of recoveries has already increased significantly. Those who recover from COVID-19 develop natural immune systems in their blood against the disease. Therefore, their blood plasma contains COVID-19 antibodies that can be used to prepare improved plasma products to treat the other patients with the disease. As statistics emphasize, only 1.88% of those who recovered donated blood plasma. Accordingly, it is essential to adopt policies to encourage recovered people to donate plasma. An apheresis method seems to be a good option to meet the purpose. After a blood component (plasma in this case) is separated through special equipment, the rest of the components are returned to the donor's bloodstream. Also, the quantity of the product obtained in this method is higher than that in the usual method of donating and producing the product (i.e., random method). In addition, through apheresis, it is possible to improve the donation of all blood products; since blood is not an ordinary material, its unique characteristics and the supply chain that it requires complicate the issue and may ultimately lead to a shortage of blood and a growth in the death rate. In addition, expired blood is often not accepted; blood donors are an infrequent asset, and donations have to occur at specific intervals. Even after eligible volunteers apply, only a few of them (5%) refer to donation sites. These conditions emphasize the need to examine the psychological factors involved in the issue and the ways to motivate donors. Of the most important features of a BSC, one may refer to the relatively irregular supply of donated blood, uncertain demand for blood products, mismatched supply and demand, and, above all, perishability of blood products.

So far, as the literature suggests, many studies have dealt with BSCs and the various processes involved in them, including inventory management, location, distribution, blood transfusion, planning for critical situations, and selection of solution approaches [10]. However, to the best of the authors' knowledge, as a significant research gap, little research has been done on improving the overall efficiency of BSCs and its levels, including donors and various blood facilities, in the face of epidemics. The main purpose of the current study is to present a multiobjective supply chain formulation for blood products with the aim of improving the attractiveness of blood centers during the COVID-19 epidemy. Accordingly, by optimizing the overall cost and the attractiveness of blood donation centers, an attractive efficient environment is provided. It can help to remove barriers to blood donation and improve blood health.

The main scope of the research is all the private and public institutions that are directly or indirectly related to both the control and treatment of COVID-19 as well as blood donation and transfusion. The leading institution involved in the campaign against coronavirus is the World Health Organization (WHO). Its goal is to achieve the highest level of health for all people [11].

Due to the disruption of BSC networks during the pandemic outbreak, blood donation has been encouraged and supported by the World Health Organization, the International Blood Transfusion Society, the International Union of Blood Donors, and the International Federation of Red Cross Societies. They are directly involved in attracting blood donation volunteers, implementing educational programs to raise the public awareness of blood donation, especially in the current critical situation, establishing and managing all blood units and facilities, and, in general, providing adequate healthy blood and its products for all patients. Accordingly, a two-objective mathematical planning model is designed for selected provincial centers. The first objective minimizes the costs of the entire supply chain network. This function addresses the cost of transporting blood collection equipment to desired places; the cost of setting up regional and local blood centers; the cost of collecting blood in each of the mobile, local, and regional blood collection centers; the cost of blood transfer from one center to another; the cost of producing the product in regional blood centers; the cost of maintaining the blood in regional blood centers and the points of demand; and the penalty on blood expiration in the places of demand. The second objective seeks to maximize the attractiveness of blood centers. What motivates this function is the reduced number of patients for blood donation due to the spread of the virus, the disturbed supply of blood supply, and the inadequate response of patients to calls for donation. Therefore, efforts are being made to adopt incentive policies such as advertisement and public awareness, reduction of the time of the blood donation process under the tension for coronavirus transmission, better implementation of health protocols by blood centers, and better staff performance to enhance the attractiveness of those centers. The present study seeks to achieve these goals with the assumption that the conformity of the conditions in blood donation centers with the donors' expectations has a positive effect on their motivation.

The costs and shortages will be reduced if proper temporary locations are determined for blood collection facilities and new local or regional blood centers are constructed. To this end, the capacity of the blood centers and the attractiveness of transmission centers should be taken into consideration too.

In general, the study is conducted to analyze the following question:

(a) To what extent does the adaptation of BSCs to the critical conditions resulting from the spread of COVID-19 play a role in controlling the disease and reducing the disorders in those chains?

(b) How do the attractiveness of blood centers, public awareness, adherence to health protocols, and better employee performance affect the demand response?

(c) Can separate mobile facilities operating through apheresis increase the donation of blood for plasma production?

The main contributions and highlights of the current study are as follows:

(i) A two-objective mathematical model to minimize the costs of the entire supply chain network and maximize the attractiveness of the blood collection centers (BCCs)

(ii) Taking certain strategies into account for the proper establishment of new local blood collection centers (BCCs) and mobile BCCs

(iii) Arranging the means of transportation for the effective transfer of blood products to the provincial centers of the candidate country and setting various incentive policies for blood donation

(iv) Considering a comprehensive practical case study. It is studied in a framework of two five-day periods and two coronary state scenarios of equal probability. However, due to the large bulk of the data as well as the duplication of cases, the case study is examined only for one period and one scenario

2. Literature Review

After proving the prevalence of the current epidemic as a unique type of disruption risk for supply chains, Ivanov [12] predicted the effects of this epidemic on the performance of supply chains globally. Using simulations, he examined the short-term and long-term effects of an epidemic on supply chains. In another study [13], Ivanov used the game theory to analyze interconnected supply networks (networks with high connectivity and resilience) and investigate the survival and resilience of those networks. Ivanov and Das [14] provided valuable insights by minimizing the harmful effects of the coronavirus on the resilience of supply chain networks. By considering the speed of the spread of the disease, distribution and disruption in the market, the duration of production, and the decrease in demand, they simulated the effects of the disease outbreak on global supply chain networks. Finally, they emphasized the importance of creating flexible and up-to-date supply chains in order to dynamically allocate supplies and demands as well as redesign global supply chains. Baesler et al. [15] investigated the management of inventory and distribution through a supply chain in order to analyze the inventory policies of blood products in a regional blood center. To this end, they used a discrete simulation model without performing mathematical modeling for activities such as blood donation, testing, and product production. Duan et al. [16] provided a red blood cell supply chain at the hospital level with eleven departments designed in an MIP model. They adjusted the inventory and the optimal allocation of blood to each department with the aim of minimizing costs, scarcity, and blood loss. The results suggested a 72% reduction in anemia, a 90% reduction in blood loss, and the saving of 108,540 monetary units (MU). Rajendran and Ravindran [17] examined platelet ordering policies at the hospital level using random MIP models and innovative approaches to reduce wastage. Hosseinifard and Abbasi [18] studied the effect of inventory concentration on the stability of BSCs at both blood bank and hospital levels, intending to minimize blood wastage and shortage. Ghandforoush and Sen [19] designed a BSC network for the optimal transfer of platelets from regional centers to hospitals as two separate levels. A nonconvex planning model served the purpose.

By applying dynamic simulation and the Taguchi method, Zahraee et al. [20] designed a robust blood supply chain system to improve the blood supply chain efficiency. Habibi-Kouchaksaraei et al. [21] solved the problem of locating facilities to minimize the costs and shortage of blood. They presented a BSC network with the three levels of collection, processing, and distribution in crises. Ramezanian and Behbodi [22] designed a dynamic location problem in a three-level blood supply network, including donors, blood donation bases (fixed and mobile), and blood centers. They did it with only one goal in mind from the donors' point of view. As the results indicated, in order to reduce costs, bases should be constructed close to blood centers. To supply whole blood in the event of a crisis, Hosseini et al. [23] proposed a novel biobjective mixed-integer linear programming for a blood supply chain network design under socioeconomic and COVID-19 considerations. Hosseini et al. [23] also provided a stable BSC network for red cells, platelets, and plasma at all levels with the aim of optimizing the costs of blood substitution and shortage in addition to other regular goals.

According to the most relevant mentioned leading works, the state-of-the-art and an updated literature review can be represented in Table 1.

Numerous factors can affect the process of blood transfusion and blood donation. In this regard, it is necessary to plan and create strategies to enhance public motivation to donate blood. Accordingly, an efficient approach is designed in the present study to optimize the overall cost and the attractiveness of blood donation centers. Indeed, an attractive environment can help to remove barriers to blood donation and improve blood health.

3. Problem Description

The present study introduces a four-level BSC network with several components including donors, regional blood centers, mobile and fixed blood centers, and demand points. The network makes provisions for the critical conditions resulting from the spread of COVID-19 and meets the particular requirements of the chain. There are a few issues to consider in a BSC. First of all, blood products are highly perishable. Secondly, different blood products, including platelets, plasma, and red blood cells, have different lifespans. During the current pandemic, the plasma of people recovering from coronary heart disease is highly required. Figure 1 presents the proposed BSC network schematically. After the optimal location of the mobile facility is specified, the first step is to collect blood from each regular or improved donor by assigning each one to the relevant facility (simple or apheresis). At this level of the supply chain, it is significant to consider incentive and educational policies, ensure the compliance with health protocols by managers, raise the public awareness and attract more donors, and, as a result, improve the second objective, namely, the attractiveness of the centers. Once the collected blood is sent to the regional centers, the processes of testing, product production, storage, and distribution are performed at the demand points.

The main assumptions of the proposed model are as follows:

(1) Mobile facilities are in local blood centers and potential areas while there are hospitals as well

(2) Donors are a group of people dispersed in an area, and it is impossible to design a blood collection program for each person

(3) Donors are divided into regular and improved groups

(4) Donors who have recovered from COVID-19 only go to apheresis centers to donate plasma

(5) Mobile facilities receive blood from different donor groups only by apheresis

(6) Regional blood centers are equipped with both simple and apheresis methods

(7) It is possible to store different products in hospitals and regional blood centers, while it is not possible in mobile facilities and local centers

(8) The age of blood products will be specified from the production time in regional centers

(9) Blood products with a lifespan of fewer than two days will not be sent from regional centers to the regional points of demand

(10) Depending on the type of each center and the data collected from the Blood Transfusion Organization (BTO) of a given country, the model is solved with the capacity parameters of each facility determined in advance

(11) Blood expiration has a penalty cost

(12) In the face of some uncertain parameters, the stochastic programming approach is used. So, scenarios with a definite probability are used in a discrete case, and normal log distribution is practiced in a continuous case

Table 1: The literature of the proposed blood supply chain network under the COVID-19 epidemy.

Authors (year)	Location	Allocation	Inventory	Uncertainty	Objectives: Single objective	Multiobjective	Modeling approach	Solution approach	Normal/improved blood groups	Network's element: Mobile blood centers	Local blood centers	Regional blood centers
Ghandforoush and Sen (2010) [19]	✓	✓	✓		✓		S		✓			✓
Baesler et al. (2014) [15]	✓	✓	✓		✓		S		✓			✓
Zahraee et al. (2015) [20]	✓	✓			✓		DS		✓			✓
Hosseinifard and Abbasi (2018) [18]	✓	✓	✓	✓		✓	SP		✓			✓
Rajendran and Ravindran (2017) [17]	✓	✓	✓	✓	✓		SP	H	✓		✓	✓
Duan et al. (2018) [16]	✓	✓			✓		DP		✓			✓
Habibi-Kouchaksaraei et al. (2018) [21]	✓	✓	✓	✓		✓	SP	MH	✓		✓	✓
Ramezanian and Behbodi (2018) [22]	✓	✓		✓	✓		DP	E	✓	✓	✓	
Yahia (2020) [7]	✓	✓	✓	✓	✓		RP	H	✓		✓	✓
Hosseini et al. (2023) [23]	✓	✓		✓	✓		PP	H	✓		✓	✓
Abdolazimi et al. (2023) [1]	✓	✓	✓	✓		✓	SP	E	✓			✓
Asgharizadeh et al. (2023) [2]	✓	✓		✓		✓	SP	H	✓	✓		
Hosseini et al. (2023) [23]	✓	✓		✓		✓	RPP	MH	✓		✓	
Current study	✓	✓	✓	✓		✓	SP	E	✓	✓	✓	✓

Note: DP: deterministic programming, E: exact, H: heuristic, MH: metaheuristic, PP: possibilistic programming, RPP: robust possibilistic programming, S: simulation, DS: dynamic simulation, SP: stochastic programming.

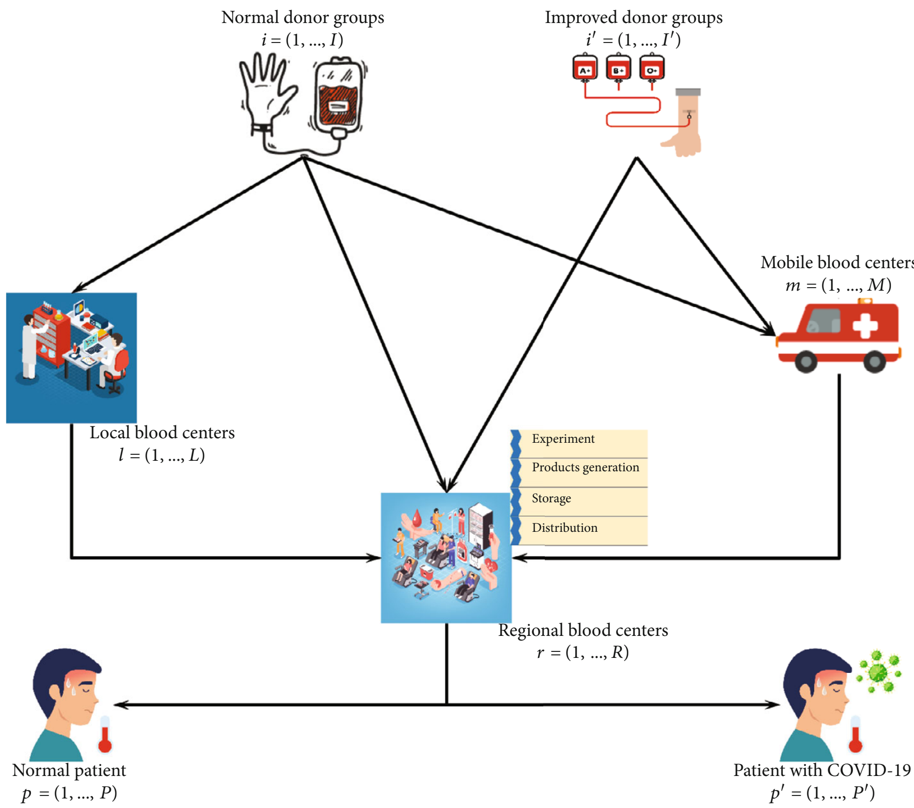


Figure 1: A blood supply chain network under the COVID-19 epidemy.

3.1. Mathematical Formulation. The proposed MIP formulation of the defined multilevel BSC is formulated as follows:

$$\text{Min } Z_1 = \sum_n \psi_n,$$

$$\psi_1 = \sum_l \text{Fa}_l.\text{YL}_l,$$

$$\psi_2 = \sum_r \text{Fb}_r.YR_r,$$

$$\psi_3 = \sum_{m'} \sum_{m'' \neq m'} \sum_t \sum_s \pi^s.\text{Fc}_{m'm''t}.\text{MV}^s_{m'm''t},$$

$$\psi_4 = \sum_i \sum_m \sum_l \sum_r \sum_p \sum_t \sum_s \pi^s.\text{Oa}_{\text{ipt}} .\left(\text{XA}^s_{\text{impt}} + \text{XB}^s_{i'\text{lp}_1 t} + \text{XC}^s_{\text{irpt}}\right), \tag{1}$$

$$\psi_5 = \sum_m \sum_l \sum_r \sum_h \sum_p \sum_a \sum_k \sum_t \sum_s \pi^s.\text{Ta}_{\text{pt}} .\left(\text{Dd}_{\text{mr}}.\text{XD}^s_{\text{mrpt}} + \text{De}_{\text{lr}}.\text{XE}^s_{\text{lrp}_1 t} + \text{Dh}_{\text{rh}}.\text{XG}^s_{\text{rhpakt}}\right),$$

$$\psi_6 = \sum_r \sum_{p \neq p_1} \sum_t \sum_s \pi^s.\text{Pa}_{\text{pt}}.\text{PR}^s_{\text{rpa}'t},$$

$$\psi_7 = \sum_r \sum_h \sum_p \sum_a \sum_k \sum_t \sum_s \pi^s.\text{Hc}_{\text{pt}}.\left(\text{IR}^s_{\text{rpat}} + \text{IH}^s_{\text{hpakt}}\right),$$

$$\psi_8 = \sum_h \sum_p \sum_a \sum_t \sum_s \pi^s.\text{Ea}_{\text{hpat}}.\text{EX}^s_{\text{hpat}},$$

$$\text{Max } Z_2 = \sum_w \sum_t \sum_s \pi^s.\text{AT}^s_{\text{wt}}. \tag{2}$$

Subject to

$$\sum_{p \neq p_1} \text{XA}^s_{\text{impt}} \leq \varphi \text{ZA}^s_{\text{imt}} \quad \forall i, m, t, s, \tag{3}$$

$$\text{XB}^s_{i'\text{lp}_1 t} \leq \varphi\, \text{ZB}^s_{i'\text{lt}} \quad \forall i', l, p_1, t, s, \tag{4}$$

$$\sum_p \text{XC}^s_{\text{irpt}} \leq \varphi\, \text{ZC}^s_{\text{irt}} \quad \forall i, r, t, s, \tag{5}$$

$$\sum_r \sum_{p \neq p_1} \text{XD}^s_{\text{mrpt}} \leq \varphi \sum_{m'} \text{MV}^s_{m',m,t}, \forall m, t, s, \tag{6}$$

$$\sum_m \sum_{p \neq p_1} \sum_t \sum_s \text{XD}^s_{\text{mrpt}} \leq \varphi\, YR_r \quad \forall r, \tag{7}$$

$$\sum_r \sum_t \sum_s \text{XE}^s_{\text{lrp}_1 t} \leq \varphi\, \text{YL}_l \quad \forall l, p_1, \tag{8}$$

$$\sum_l \sum_t \sum_s \text{XE}^s_{\text{lrp}_1 t} \leq \varphi\, \text{YR}_r \quad \forall r, \tag{9}$$

$$\sum_h \sum_p \sum_a \sum_k \sum_t \sum_s \text{XG}^s_{\text{rhpakt}} \leq \varphi\, \text{YR}_r \quad \forall r, \tag{10}$$

$$\text{ZA}^s_{\text{imt}}.\text{Da}_{\text{im}} \leq \text{Ra}_m \sum_{m'} \text{MV}^s_{m'\text{mt}} \quad \forall i, m, t, s, \tag{11}$$

$$\mathrm{ZB}^{s}_{i'\mathrm{lt}}.\mathrm{Db}_{i'l} \le \mathrm{Rb}_l.\mathrm{YL}_l \quad \forall i', l, t, s, \tag{12}$$

$$\mathrm{ZC}^{s}_{\mathrm{irt}}.\mathrm{Dc}_{\mathrm{ir}} \le \mathrm{Rc}_r.\mathrm{YR}_r \quad \forall i, r, t, s, \tag{13}$$

$$\sum_{m'} \mathrm{MV}^{s}_{m'm''t} \le 1 \quad \forall m'', t, s, \tag{14}$$

$$\sum_{m''} \mathrm{MV}^{s}_{m'm''t} \le 1 \quad \forall m', t, s, \tag{15}$$

$$\sum_{m''} \mathrm{MV}^{s}_{m'm'',t} \le \sum_{m} \mathrm{MV}^{s}_{\mathrm{mm}',t-1} \quad \forall m', t \ge 2, s, \tag{16}$$

$$\sum_{m} \mathrm{ZA}^{s}_{i'\mathrm{mt}} + \sum_{l} \mathrm{ZB}^{s}_{i'\mathrm{lt}} + \sum_{r} \mathrm{ZC}^{s}_{i'\mathrm{rt}} \le 1 \quad \forall i', t, s, \tag{17}$$

$$\sum_{m} ZA^{s}_{i''\mathrm{mt}} + \sum_{r} \mathrm{ZC}^{s}_{i''\mathrm{rt}} \le 1 \quad \forall i'', t, s, \tag{18}$$

$$\mathrm{Po}_p \cdot \left(\sum_{l} \mathrm{XE}^{s}_{\mathrm{lrp}_1 t} + \sum_{i'} \mathrm{XC}^{s}_{i'\mathrm{rp}_1 t} \right) = \mathrm{PR}^{s}_{\mathrm{rpa}'t} \quad \forall r, p \ne p_1, p_5, a', t, s, \tag{19}$$

$$\sum_{m} \mathrm{XD}^{s}_{\mathrm{mrpt}} + \sum_{i} \mathrm{XC}^{s}_{\mathrm{irpt}} = \mathrm{PR}^{s}_{\mathrm{rpa}''t} \quad \forall r, p \ne p_1, a'', t, s, \tag{20}$$

$$\sum_{i} \mathrm{XA}^{s}_{\mathrm{impt}} \le \mathrm{Sb}_{\mathrm{pt}} \quad \forall m, p, t, s, \tag{21}$$

$$\sum_{i'} \mathrm{XB}^{s}_{i'\mathrm{lp}_1 t} \le \mathrm{Sa}_{\mathrm{lp}_1 t} \quad \forall l, t, s, \tag{22}$$

$$\sum_{a} \mathrm{PR}^{s}_{\mathrm{rpat}} \le \mathrm{Sc}_{\mathrm{rpat}}.\mathrm{YR}_r \quad \forall r, p, t, s, \tag{23}$$

$$\sum_{a} \mathrm{IR}^{s}_{\mathrm{rpat}} \le \mathrm{Se}_{\mathrm{rpat}}.\mathrm{YR}_r \quad \forall r, p, t, s, \tag{24}$$

$$\sum_{a} \sum_{k} \mathrm{IH}^{s}_{\mathrm{hpakt}} \le \mathrm{Sk}_{\mathrm{hpat}} \quad \forall h, p, t, s, \tag{25}$$

$$\sum_{i} \mathrm{XA}^{s}_{\mathrm{impt}} = \sum_{r} \mathrm{XD}^{s}_{\mathrm{mrpt}} \quad \forall m, t, s, \tag{26}$$

$$\sum_{i'} XB^{s}_{i'\mathrm{lp}_1 t} = \sum_{r} \mathrm{XE}^{s}_{\mathrm{lrp}_1 t} \quad \forall l, t, s, \tag{27}$$

$$\mathrm{IR}^{s}_{\mathrm{rpat}} = \mathrm{IR}^{s}_{\mathrm{rpa},t-1} + \mathrm{PR}^{s}_{\mathrm{rpat}} - \sum_{h} \sum_{k \ge 2} \mathrm{XG}^{s}_{\mathrm{rhpakt}} \quad \forall r, p, a, t, s, \tag{28}$$

$$\mathrm{IH}^{s}_{\mathrm{hpakt}} = \mathrm{IH}^{s}_{\mathrm{hpa},k-1,t-1} + \sum_{r} \mathrm{XG}^{s}_{\mathrm{rhpakt}} - \sum_{r} \mathrm{XH}^{s}_{\mathrm{rhpakt}} \quad \forall h, p, a, k \ge 2, t, s, \tag{29}$$

$$\sum_{r} \sum_{k} \mathrm{XH}^{s}_{\mathrm{rhpakt}} + \mathrm{EX}^{s}_{\mathrm{hpat}} + \mathrm{SH}^{s}_{\mathrm{hpat}} = \mathrm{Dm}^{s}_{\mathrm{hpat}} \quad \forall h, p, a, t, s, \tag{30}$$

$$\sum_{r} \sum_{k} \mathrm{XH}^{s}_{\mathrm{rhpakt}} \ge (\mathrm{AT}^{s}_{\mathrm{wt}}/1000).\mathrm{Dm}^{s}_{\mathrm{hpat}} \quad \forall h, p, a, w, t, s, \tag{31}$$

$$\sum_{i} \mathrm{XA}^{s}_{\mathrm{impt}} \le \mathrm{Dr}^{s}.\mathrm{Pop}_m.(\mathrm{AT}^{s}_{\mathrm{mt}})/\mathrm{Ub}_m \quad \forall m, p, t, s, \tag{32}$$

$$\mathrm{AT}^{s}_{\mathrm{mt}} = \tau_m^{-S\tau_m}.\sigma_m^{S\sigma_m}.\vartheta_m^{S\vartheta_m}.\sum_{m'} \mathrm{MV}^{s}_{m'\mathrm{mt}} \quad \forall m, t, s, \tag{33}$$

$$\sum_{i'} \mathrm{XB}^{s}_{i'\mathrm{lp}_1 t} \le \mathrm{Dr}^{s}.\mathrm{Pop}_l.(\mathrm{AT}^{s}_{\mathrm{lt}})/\mathrm{Ub}_l \quad \forall l, t, s, \tag{34}$$

$$\mathrm{AT}^{s}_{\mathrm{lt}} = \tau_l^{-S\tau_l}.\sigma_l^{S\sigma_l}.\vartheta_l^{S\vartheta_l}.\mathrm{YL}_l \quad \forall l, t, s, \tag{35}$$

$$\sum_{i} \mathrm{XC}^{s}_{\mathrm{irpt}} \le \mathrm{Dr}^{s}.\mathrm{Pop}_r \cdot \frac{(\mathrm{AT}^{s}_{\mathrm{rt}})}{\mathrm{Ub}_r} \forall r, p, t, s, \tag{36}$$

$$\mathrm{AT}^{s}_{\mathrm{rt}} = \tau_r^{-S\tau_r}.\sigma_r^{S\sigma_r}.\vartheta_r^{S\vartheta_r}.\mathrm{YR}_r \quad \forall r, t, s, \tag{37}$$

$$\mathrm{YL}_l, \mathrm{YR}_r, \mathrm{ZA}^{s}_{\mathrm{imt}}, \mathrm{ZB}^{s}_{i'\mathrm{lt}}, \mathrm{ZC}^{s}_{\mathrm{irt}}, \mathrm{MV}^{s}_{m'm''t} \in \{0, 1\}, \tag{38}$$

$$\mathrm{XA}^{s}_{\mathrm{impt}}, \mathrm{XB}^{s}_{i'\mathrm{lp}_1 t}, \mathrm{XC}^{s}_{\mathrm{irpt}}, \mathrm{XD}^{s}_{\mathrm{mrpt}}, \mathrm{XE}^{s}_{\mathrm{lrp}_1 t}, \mathrm{XG}^{s}_{\mathrm{rhpakt}}, \mathrm{XH}^{s}_{\mathrm{rhpakt}}, \mathrm{PR}^{s}_{\mathrm{rpat}}, \mathrm{SH}^{s}_{\mathrm{hpat}}, \mathrm{EX}^{s}_{\mathrm{hpat}}, \mathrm{IR}^{s}_{\mathrm{rpat}}, \mathrm{IH}^{s}_{\mathrm{hpakt}}, \mathrm{AT}^{s}_{\mathrm{wt}} \ge 0, \mathrm{int}. \tag{39}$$

Objective function (1) minimizes the costs of the entire supply chain network. They include the cost of setting up local and regional centers, the cost of moving mobile blood collection equipment to any place, the cost of collecting blood in each of the local and regional collection centers, the cost of transferring blood from one center to another, the cost of producing the product in the regional centers, the cost of maintaining the blood in the regional centers and the demand points, and the penalty of extra blood expiration in the demand points. Objective function (2) is to maximize the attractiveness of blood centers, which is calculated according to the corresponding constraints, advertising budget, staff experience, the time required for blood donation, and donors' sensitivity to these factors.

Constraint (3) states that blood donation is possible in any mobile collection facility if donors are assigned to that facility. Constraint (4) states that whole blood donation is possible at local blood centers if regular donors are assigned to this center. Constraint (5) emphasizes that the donation of whole blood or blood products to regional blood centers is possible if donors are allocated to those centers. Constraints (6) and (7) state that the allocation of mobile collection facilities to regional centers is possible if both centers are established. Constraints (8) and (9) mean that the allocation of local centers to regional centers is possible if both local and regional centers are established. Constraint (10) indicates that hospitals are only allocated to the regional centers that have been set up. Constraints (11)–(13) indicate that donors are served according to the maximum coverage radius. Constraints (14) and (15) show that only one mobile blood collection facility must go anywhere and that each mobile facility can only go to one place. Constraint (16) emphasizes that the movement of a mobile facility from the first to the second place is possible if that facility was located in the first place in the previous period. Constraints (17) and (18) state that each donor group can be allocated only to one of the associated centers. Constraints (19) and (20) calculate the amount of each blood product produced by simple and apheresis methods and collected in each regional center. Constraints (21) and (22) specify the capacity of mobile collection facilities and local centers to collect each of the blood products in each period, respectively. Constraint (23) specifies the capacity of regional centers to collect and produce blood products by simple or apheresis methods in each period. Constraints (24) and (25), respectively, express the capacity of each warehouse in the regional blood centers and the demand points for the storage of each blood product according to the method of production. Constraint (26) balances the input and output of mobile blood collection facilities. Constraint (27) balances the outflow and inflow of local blood centers. Constraints (28) and (29) establish an inventory balance for regional blood centers and demand points, respectively. Constraint (30) calculates the shortage of each blood product made by a production method at the demand point at the end of each period. Constraint (31) indicates the minimum amount of demand that must be met and varies according to the attractiveness of each center. Constraints (32)–(37) calculate the amount of blood donation in each blood center according to the attractiveness of that center. Finally, constraints (38) and (39) demonstrate the status of the decision variables.

4. Solution Methodology

In order to solve the proposed multiobjective mathematical formulation, the improved version of the augmented ε-constraint method (AUGMECON2) is applied to attain efficient solutions. In multiobjective models, a unique solution cannot be found after the problem is solved; instead, there is a set of plausible solutions. The multiobjective literature is called the Pareto frontier [24]. In fact, in such cases, the goal is to find a set of points (Pareto frontier) and present them to the decision-maker to choose one based on his preferences. For the decision-maker to express his preferences according to the solution obtained and the technical limitations of the problem, interactive multiobjective planning approaches are more appropriate than other approaches. By employing these methods, an acceptable proximity to Pareto optimal solutions can be achieved, facilitating the decision-making process in situations where one is faced with multiobjective problems. This study is based on the solving methods of AUGMECON2, as explained below.

The AUGMECON2 is one of the well-known approaches, and also, it is a compelling solution for dealing with multiobjective problems which many studies have been used.

Nowadays, decision-makers and practitioners frequently have to cope with several objectives that are conflict with each other. Generally, multiobjective problems can be solved either by Pareto-based or weighted sum methods. Pareto-based methods make a balance among objectives by creating a Pareto set, while, weighted sum methods turn the multiobjective problem into a single-objective problem and solve the problem. In this study, we try to establish a balance among all of the objective functions. So, to avoid prioritizing one objective over the others, the AUGMECON2 is used to create Pareto solutions. Mavrotas and Florios [24] proposed it to cover the traditional ε-constraint's weaknesses. As a significant positive point, it can guarantee nondominated solutions and mitigate calculational time. The AUGMECON2 works as follows:

$$\text{Max}\left(F_1(x) + e \times \left(\frac{R_2}{u_2} + 10^{-1} \times \frac{R_3}{u_3} + \cdots + 10^{-(P-2)} \times \frac{R_P}{u_P}\right)\right), \tag{40}$$

Subject to

$$F_k(x) - R_k = \varepsilon_k, \quad \forall k \in \{2, \cdots, P\}. \tag{41}$$

In equation (40), $F_k(x)$ is the objective function that must be optimized. The parameter ε_k represents the right-hand side for the k^{th} objective. Plus, e takes a value between 10^{-6} and 10^{-3}. R_k indicates the surplus variable, and the range parameters are shown by $u_1, u_2, \cdots, u_P$. The execution steps of AUGMECON2 are as follows:

(I) Making the payoff table using lexicographic optimization

(II) Setting a lower bound (lb_k) and obtaining ranges (u_k), for every objective k following the payoff table

(III) Converting the range of the k^{th} objective to identical intervals (h_k)

(IV) The right side of the related constraint in the predetermined objective is gained through the equation $\varepsilon_k = \text{lb}_k + i_k \times \text{step}_k$. i_k is the counter for the k^{th} objective, and step_k is calculated as $\text{step}_k = u_k / h_k$

(V) Solve the model

(VI) In each iteration, the coefficient S_k is calculated as $b = \text{int}\,(R_k/\text{step}_k)$

(VII) Generating the Pareto set according to the number of grid points and bypass

Figure 2 depicts the flowchart of the proposed AUGMECON2.

5. Results and Discussions

In this section, the implementation results of the proposed mathematical model are presented. At first, for validating and verifying, the mathematical model is implemented in several numerical examples and by the proposed solution method, and the results are compared. In the following, the solution method implements the mathematical model in a real case study. Accordingly, the model is run in the presence of COVID-19, and the results are compared. Therefore, to compare the results, the effect of several parameters on the values of decision variables and objective functions is investigated to the proposed mathematical model. Then, several sensitivity analyses are performed, and the impact of essential parameters of the model on the

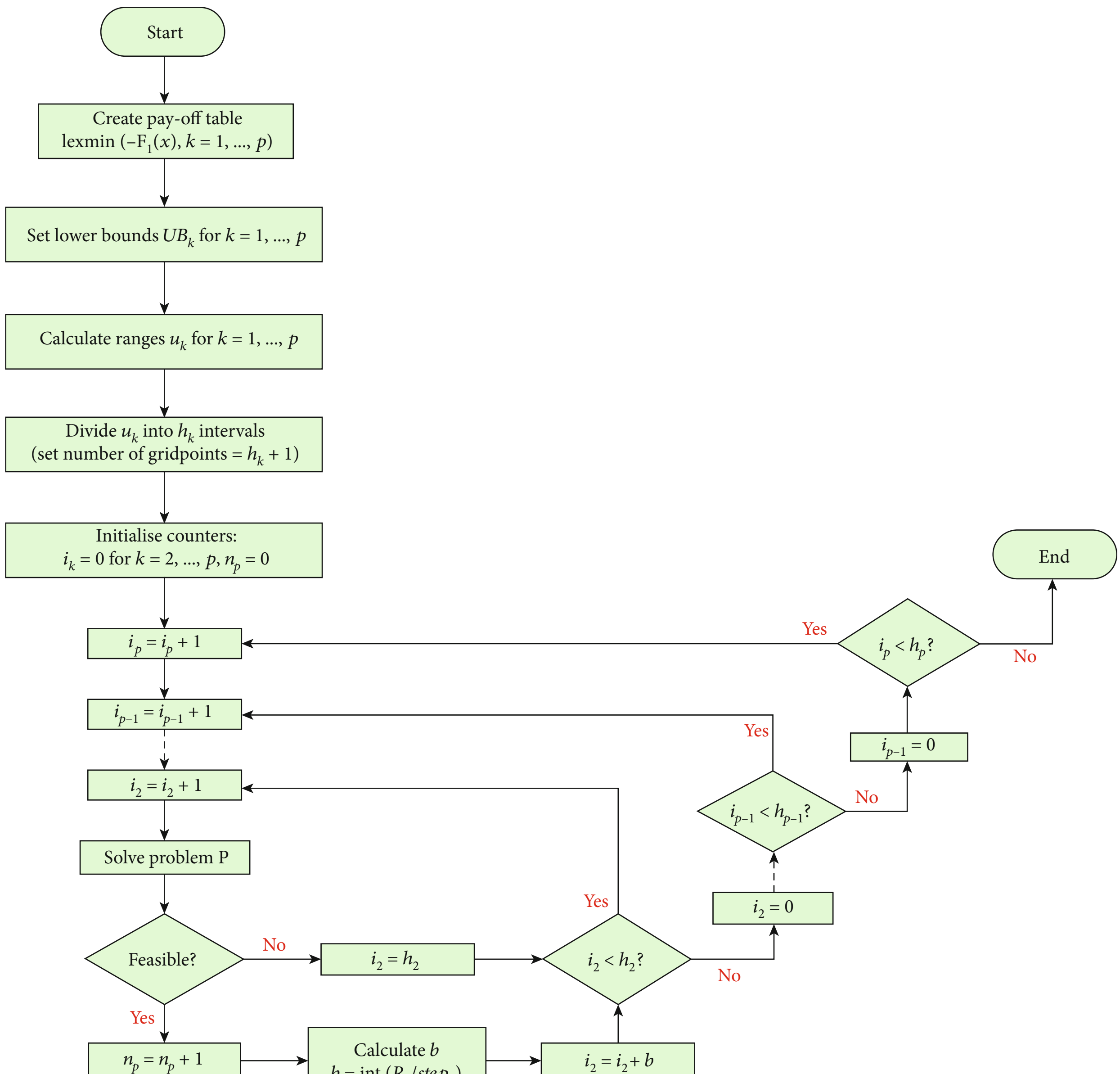


Figure 2: The flowchart of the proposed AUGMECON2.

objective functions is analyzed. Finally, management insights related to the sensitivity analysis results are presented.

5.1. Numerical Examples of Their Results. This section is aimed at validating the proposed model and approaches. For validating and comparing them in the productive Pareto solutions, 10 various numerical examples are presented. Then, the outcomes are compared. GAMS 24.1.3 software and a PC with CPU Intel Core i7 and 16 GB RAM have been used. Two indicators are used, including the two objective functions calculated in the suggested solution method. The proposed approach is analyzed in various numerical examples in different dimensions, as represented in Table 2. The sizes of the designed numerical instances are presented as follows.

The other parameters utilized in this numerical example are represented in Table 3.

The results of applying the proposed AUGMECON2 method to the numerical examples are illustrated in Table 4. The values obtained through solving the samples for the three ε values of 0, 0.5, and 1 are presented as follows.

According to Table 4, it can be concluded that the value of ε affects on the values of two objective functions, such that by growing the value of ε, the values of objective functions increase. The obtained values of objective functions emphasize the performance of the proposed approach.

5.2. Case Study

5.2.1. Descriptions and Analysis. Iran, with an area of 1,648,000 km^2, is the 17$^{\text{th}}$ largest country in the world. It

Table 2: Specifications of the samples.

Indicators	Sample instance number									
	1	2	3	4	5	6	7	8	9	10
Ordinary donor group	2	4	6	8	10	14	16	18	19	20
Improved donor group	2	4	6	8	10	14	16	18	15	18
Temporary facilities	3	5	7	9	11	8	7	9	7	8
Local centers	4	6	8	10	12	9	8	10	12	10
Regional centers	4	6	8	10	12	9	8	10	9	14
Hospitals	2	4	6	8	10	8	7	10	12	15
Blood product	5	5	5	5	5	5	5	5	5	5
Life of each product	5	5	5	5	5	5	5	5	5	5
Blood collection method	2	2	2	2	2	2	2	2	2	2
Period	1	1	2	2	1	3	2	2	2	1
Corona status scenarios	1	2	2	2	2	2	3	1	2	2

Table 3: The values of the parameters in the model.

Parameter	Value	Parameter	Value
Fa_l	~U (100, 150)	$Db_{i'l}$	~U (2, 15)
Fb_r	~U (150, 300)	Dc_{ir}	~U (2, 15)
$Fc_{m'm''t}$	~U (1, 3)	Dd_{mr}	~U (2, 15)
Ta_{pt}	~U (0.03, 0.035)	De_{lr}	~U (2, 15)
Oa_{ipt}	~U (0.01, 0.015)	Dh_{rh}	~U (300, 1000)
Pa_{pt}	~U (0.03, 0.06)	Ra_m	10
Hc_{pt}	~U (0.02, 0.03)	Rb_l	10
Sa_{lp_1t}	~U (132, 180)	Rc_r	10
Sb_{pt}	~U (84, 108)	Po_p	1/3
Sc_{rpat}	~U (480,600)	Ea_{hpat}	10
Se_{rpat}	~U (120, 144)	Dm^s_{hpat}	~U (40, 60)
Sk_{hpat}	~U (50, 80)	π^s	~U (0.3, 0.4)
Da_{im}	~U (2, 15)	St	0.5

Table 4: Values obtained from solving the samples.

Samples	ε	First objective function (cost, MU)	Second objective function (attractiveness of blood centers)
	0	437	80
1	0.5	440	157
	1	504	279
	0	1018	412
2	0.5	1292	640
	1	2322	863
	0	2145	449
3	0.5	2145	614
	1	2254	881
	0	3291	807
4	0.5	3867	1173
	1	6423	1641
	0	1688	499
5	0.5	2248	680
	1	2821	861
	0	3860	1131
6	0.5	5092	1996
	1	7385	2879
	0	2405	676
7	0.5	3070	1301
	1	4609	1924
	0	3538	758
8	0.5	4706	1342
	1	7531	1935
	0	2423	462
9	0.5	2839	587
	1	4573	952
	0	2457	480
10	0.5	3522	732
	1	4670	980
	0	2327	575
Mean	0.5	2922	922
	1	4309	1319

consists of 1245 cities and 31 provinces with about 85 million people. According to the experts in the Blood Transfusion Organization (BTO) of Iran, the current BSC network in Iran needs to be improved as much as possible. In 2018, 3,600,000 units of blood and blood products were transferred to 800 hospitals; however, in March 2020, with the decrease in donor visits due to the spread of COVID-19, the number of blood donations in the whole country decreased by 35% [9]. After the situation was managed through vaccine injection, the total amount of the donated blood in Iran increased by 7% in the first half of 2021 compared to the previous year. The blood reserves of the country are now about 20 percent lower than last year [5]. In addition, Iran is among the countries that started the plasma therapy of COVID-19 patients from the earliest days, but reports indicate that the amount of plasma received from coronary arteries in Iran is about half the required amount. New protocols concerning 14 days after vaccination and 28 days after coronary artery diseases have been effective in reducing the disease.

Considering the challenges that the Blood Transfusion Organization of Iran is faced with, providing an efficient approach in the form of a comprehensive mathematical formulation can greatly help to improve the efficiency of the blood chain network and its management. In the mathematical model proposed here, it is desired to determine the best locations to set up blood centers with specific capacities. The aim is to have a network with low costs and high attractiveness with some influential factors taken into account such as advertisement and blood donation time.

Figure 3: The best locations to establish mobile, local, and regional blood centers.

The proposed formulation determines the optimal type and location of each center according to the system costs, the capacity of each center, and the demand for blood. It also sets collection methods (simple and apheresis) and the decision variables, as described in Section 3. The present study is designed in a framework of two five-day periods and two coronary state scenarios of equal probability. However, due to the large bulk of the data as well as the duplication of cases, the performance of the model is examined only for one period and one scenario. In this case, the hospitals in each province are specified as demand node. Also, the blood supply is calculated due to certain parameters such as the population of each province, the percentage of blood donation, and the capacity and attractiveness of the blood centers. Besides, transportation costs are calculated based on the distance between the blood centers, and the values of the other parameters are extracted from the blood transfusion organization.

As mentioned, in the first step, the proposed formulation seeks to find the best location to set up blood centers and facilities with different performances, including blood collection from two types of donor groups by simple and apheresis methods as well as processing, production and distribution of red cell products, platelets, plasma of regular people, and improved plasma from the corona. According to Figure 3, among 31 provincial centers in Iran, seven have been selected to set up regional blood centers, two for local centers, and four to establish mobile facilities where apheresis is practiced. It should be noted that, in some provincial centers (mainly those with larger populations), more than one facility has been set up. For example, Tehran has been selected where to set up two regional and local blood centers simultaneously, and Tabriz is selected for a regional blood center and a mobile facility. It should also be noted that the lack of a blood center in a provincial capital does not mean a shortage of blood there. This is because the products

Table 5: Population of the selected provincial centers and the characteristics of the blood centers established in each of them (M = mobile, L = local, R = regional).

Population	Provinces	Advertisement budget (MU)			Blood donation time (minute)			Staff experience (year)		
		M	L	R	M	L	R	M	L	R
7,153,309	Tehran	3	5	10	20	50	40	5	10	18
577,514	Kerman	1.5	3	5	15	35	25	2	5	11
2,307,177	Mashhad	3	4	8	20	40	30	4	9	16
477,905	Yazd	2	3	6	10	25	15	2	6	14
1,547,164	Isfahan	1	1	3	5	15	10	3	8	15
124,826	Semnan	2	2	4	10	20	15	1	6	13
1,424,641	Tabriz	1.5	2	5	10	25	20	3	8	14
1,249,942	Shiraz	1	1	4	5	10	15	3	7	17
841,145	Ahvaz	2	3	7	15	20	15	2	7	12
165,377	Bushehr	—	—	—	—	—	—	—	—	—

Table 6: The amount of the product produced in regional centers.

Regional blood center	Method of production	Blood products (blood bags)			
		Red cell (P_2)	Platelets (P_3)	Plasma type I (P_4)	Plasma type II (P_5)
Ahvaz	Simple	35	35	35	—
	Apheresis	32	34	32	40
Mashhad	Simple	61	61	61	—
	Apheresis	66	67	58	60
Tabriz	Simple	36	36	36	—
	Apheresis	65	61	59	64
Yazd	Simple	33	33	33	—
	Apheresis	29	37	30	30
Shiraz	Simple	39	39	39	—
	Apheresis	37	37	31	4
Tehran	Simple	72	72	72	—
	Apheresis	61	60	75	98
Isfahan	Simple	72	72	72	—
	Apheresis	36	36	36	36

collected in one provincial center can be transferred to the other parts of demand. Other additional required data have been provided and obtained from the "ministry of Health and treatment" and also the "Blood Transfusion Organization" of the country as shown in Tables 5–7. Moreover, the complementary data of the case study are represented in Table 8.

Table 5 presents the selected provincial centers and those established to send blood along with their population. The data are based on the latest official statistical reports. The table also reports the approximate amount of advertising budget allocated to each provincial center, the time spent for blood donation, the work experience of blood centers, and their staff according to managers' opinions and field observations.

After blood donation by different donor groups at different blood centers available in each provincial center, the final quantities of each product are sent to regional blood centers. Table 6 presents the corresponding data obtained by simple production and apheresis methods. The total blood products produced by these methods in the regional blood center of each provincial center correspond to the total amount of the blood collected in that center.

Table 7 reports the quantities of the products sent from each blood center to hospitals based on the approximate amount of the demand in each city, the type of the product, its life, and the method of production.

It should be noted that six to ten units of whole blood must be isolated by the simple blood donation method so that the platelets can be injected into patients as a task of platelet therapy. In the apheresis method, however, more and more effective platelets can be obtained from one donor. The platelet content obtained in this method is equal to the platelets of eight whole blood units donated by eight people. Accordingly, it is essential to differentiate the products based on the production method. After the data are collected from experts and according to the procedure of blood production and processing, the products obtained through the simple method and apheresis method can be transferred to demand points one day and two days after production, respectively (Table 7).

Table 7: Amount of the products (blood bags) sent to hospitals.

Hospital	Product / Method of production	Red cells (P_2) Simple	Red cells (P_2) Apheresis	Platelets (P_3) Simple	Platelets (P_3) Apheresis	Plasma type (I) (P_4) Simple	Plasma type (I) (P_4) Apheresis	Plasma type (II) (P_5) Simple	Plasma type (II) (P_5) Apheresis
h_1	Age (days)	2	4	3	1	4	2	4	4
	Number of blood bags	31	36	37	30	29	31	36	31
h_2	Age (days)	1	4	2	1	4	1	4	1
	Number of blood bags	37	32	32	32	38	37	32	31
h_3	Age (days)	1	4	4	1	5	1	4	1
	Number of blood bags	29	34	35	35	36	29	34	29
h_4	Age (days)	2	2	5	1	4	2	2	1
	Number of blood bags	30	33	35	30	30	30	33	36
h_5	Age (days)	5	4	4	5	4	5	4	1
	Number of blood bags	32	37	33	35	32	32	37	38
h_6	Age (days)	1	3	4	1	5	1	3	1
	Number of blood bags	32	33	36	30	36	32	33	35
h_7	Age (days)	1	4	2	1	2	1	4	1
	Number of blood bags	29	38	33	37	37	29	38	30
h_8	Age (days)	1	5	4	1	5	1	5	1
	Number of blood bags	35	3	30	31	34	35	3	30
h_9	Age (days)	1	4	5	1	5	1	4	1
	Number of blood bags	35	32	34	36	38	35	32	35
h_{10}	Age (days)	1	3	4	1	4	1	3	1
	Number of blood bags	37	34	41	37	38	37	34	38

5.2.2. Pareto Front. For better proximity to reality, the first objective postulates minimizing the total network costs as the main goal, and the second objective pursues maximizing the attractiveness of the centers and, thus, increasing the blood donation as a subgoal. The case study has been solved with the ε-constraint method, and the corresponding Pareto values and epsilons are presented in Figure 4 and Table 9.

Figure 4 shows the Pareto boundary obtained after the analysis of the case study.

According to Figure 4, as the second objective function increases, the value of the first objective increases too. The main goal is to reduce the cost of the entire network. In fact, a growth in the attractiveness of blood centers induces a raise in the number of donors, and, consequently, the amount of the donated blood grows. This depends on more investment at all levels of the supply chain, including collection, production, storage, and transportation. Such contrasting conditions, i.e., cost reduction and more investment, make it necessary to have a two-objective function optimization problem.

6. Sensitivity Analysis

In this section, the sensitivity of the objective functions is examined by the changing of the critical parameters, including the capacities of blood facilities, advertising, experience, and blood donation time, along with the donor influence parameters related to individual factors. It should be mentioned that, for the involvement of both objectives, the sensitivity analysis of the parameters is performed by the ε of 0.5.

6.1. Blood Facility Capacity $(\mathbf{Sa}_{\mathbf{lp}_1 t}, \mathbf{Sb}_{\mathbf{pt}}, \mathbf{Sc}_{\mathbf{rpat}}, \mathbf{Se}_{\mathbf{rpat}}, \mathbf{Sk}_{\mathbf{hpat}})$. The effects of 10% and 20% changes in the capacities of blood centers (i.e., all of $\mathbf{Sa}_{\mathbf{lp}_1 t}, \mathbf{Sb}_{\mathbf{pt}}, \mathbf{Sc}_{\mathbf{rpat}}, \mathbf{Se}_{\mathbf{rpat}}, \mathbf{Sk}_{\mathbf{hpat}}$) on the objectives are reported in Figure 5. Unexpectedly, the total attractiveness of all the blood centers and, consequently, the cost of the entire network remain constant as the capacities of blood facilities increase. This indicates that the blood centers generally have a sufficient capacity and the increase in blood donation depends on other influential factors, including incentive policies. On the other hand, it is evident that, with the reduction of capacity, the blood centers will not be able to respond to all donors. Accordingly, the amount of the donated blood and, subsequently, the operating costs will be reduced. This is because donors are not directly attracted to blood centers as the capacity of those centers increases. Some influential parameters in this regard are analyzed in the following.

6.2. Advertising and Its Effect on the Rate of Blood Donation $(\boldsymbol{\sigma_w}, \boldsymbol{S\sigma_w})$. The effects of 10% and 20% changes in the amount of advertisement on the objectives are reported in Figure 6.

It is clear that advertisement can promote the attractiveness of the centers, which also leads to more blood donation and costs. After the establishment of centers, the rate of blood donation increases if the spatial attractiveness is improved. In this case, the operating costs rise too.

The cost parameter shows the same behavior. Increased advertisements result in more attractive blood centers, which, in turn, increase the blood donation and the operating cost. In contrast, with low advertisements, the number

Table 8: The complementary data of the case study.

Parameter	Description	Value
Fa_l	The cost of setting up local blood center l	fa(l) = uniform(5, 7);
Fb_r	The cost of setting up regional blood center r	fb(r) = uniform(20, 30);
$Fc_{m'm''t}$	The cost of moving each mobile device from place m' to place m'' during t	fc(mm, mmm, t) = uniform(1, 3);
Ta_{pt}	The cost of transporting each unit of blood product p per kilometer per t	ta(t) = uniform(0.003,0.0035);
Oa_{ipt}	The cost of collecting each unit of blood product p from donor group i during t	oa(ia, m, p, t) = uniform(0.01,0.015);
Pa_{pt}	The cost of production per unit of blood product p in regional blood centers in t	pa(p, t) = uniform(0.03,0.06);
Hc_{pt}	The cost of maintaining each unit of blood product p during period t	hc(h, p, a, t) = 5;
Sa_{lp_1t}	Local blood center capacity l to collect whole blood (p_1) during period t	sa(l, p1, t) = uniformint(180,280) ;
Sb_{pt}	The capacity of mobile facilities to collect blood products p during t	sb(p, t) = uniformint(150,200);
Sc_{rpat}	The capacity of regional center r to collect and produce blood products p obtained by collection method a during period t	sc(r, p, a, t) = uniformint(480,600);
Se_{rpat}	The capacity of regional center r to store blood products p obtained by collection method a during period t	se(r, p, a, t) = 0;
Sk_{hpat}	Demand point capacity h to store blood products p obtained by collection method a during period t	sk(h, p, a, t) = 0;
Da_{im}	The amount of route between donor group i and facility m	da(i, m) = uniform(2, 15);
$Db_{i'l}$	The amount of route between donor group i' and local center l	db(i, l) = uniform(2, 15);
Dc_{ir}	The amount of route between donor group i and regional center r	dc(i, r) = uniform(2, 15);
Dd_{mr}	The amount of route between facility m and regional center r	dd(m, r) = uniform(2, 15);
De_{lr}	The amount of route between local center l and regional center r	de(l, r) = uniform(2, 15);
Dh_{rh}	The amount of route between regional center r and demand point h	de(l, r) = uniform(2, 15);
Ra_m	Maximum coverage radius of mobile facility m to serve donors	ra(m) = 10;
Rb_l	Maximum coverage radius of local center l to serve donors	rb(l) = 10;
Rc_r	Maximum coverage radius of regional center r to serve donors	rc(r) = 10;
Po_p	Percentage of blood product production p	po(p) = 1/3;
Ea_{hpat}	Expiry cost per unit of extra blood product p obtained by collection method a at the demand point h during t	ea(h, p, a, t) = 10;
Dm^s_{hpat}	Hospital demand h for blood products p obtained by collection method a during t under scenario s	Dm(s, h, p, a, t) = 30;
τ_w	Time spent on the blood donation process at blood center w	doo(ia, p1, t, s) = uniformint(500, 1000);
σ_w	Advertising budget in blood center w	doo(ia, p2, t, s) = uniformint(10000, 30000);
ϑ_w	Experience factor in blood center w	doo(ia, p3, t, s) = uniformint(0, 20);
$S\tau_w$	Donor sensitivity to time τ_w	0.7
$S\sigma_w$	Donor sensitivity to advertising σ_w	0.5
$S\vartheta_w$	Donor sensitivity to experience factor ϑ_w	0.9
Dr^s	Average donation rate under scenario s	0.65
Pop_w	The population of the area allocated to blood center w	From Table 5
Ub_w	The best productivity available in blood center w	0.85
π^s	Probability of scenario s	Phi = uniformint(0, 1);
φ	A very large number	100
ε	A number from zero to one	0, 0.5, 1

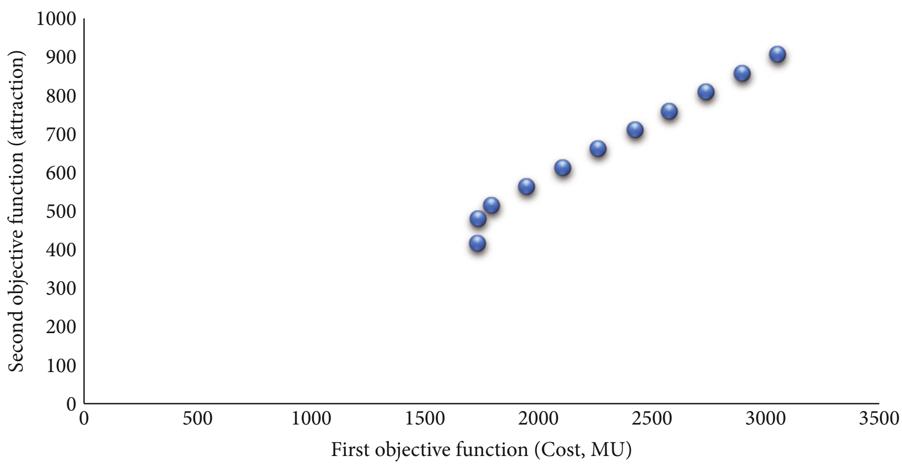


Figure 4: The Pareto boundary obtained from analyzing the case study.

Table 9: Pareto results of solving the case study problem.

The value of ε	First objective (cost, MU)	Second objective (attractiveness of blood centers)
0	1744	419
0.1	1746	483
0.2	1805	517
0.3	1959	566
0.4	2118	615
0.5	2273	664
0.6	2436	713
0.7	2587	761
0.8	2748	811
0.9	2907	859
1	3062	908

of clients cannot be expected to rise, and the operating costs decrease. These relationships are plotted in Figure 7.

6.3. Donor Experience and Effectiveness ($\boldsymbol{\vartheta_w}, \boldsymbol{S\vartheta_w}$). The effects of 10% and 20% changes in the rate of experience on the objectives are reported in Figure 8.

As in the previous section, a rise in the reputation and work experience of blood centers, as a positive parameter, enhances the attraction of those centers and, consequently, reduces the costs of the network.

As Figure 9 suggests, after the desired changes are made in the experience parameter, similar impacts are observed on individual donors.

6.4. Donor Time and Sensitivity ($\boldsymbol{\tau_w}, \boldsymbol{S\tau_w}$). First, the effects of 10% and 20% changes in the time spent for blood donation on the objective functions are reported in Figure 10.

It is evident that a longer blood donation time and, as a result, a longer waiting time lead to the reduced attraction of the donation centers. This has an adverse effect on the amount of the donated blood and the operation costs. Conversely, given the prevalence of coronavirus, the faster the blood donation process, the more attractive the centers will be for donors. Consequently, the number of donors, the amount of blood donation, and, ultimately, the total costs of the network are all positively affected.

Assuming that the time required for blood donation is constant, the donor's sensitivity to time and the effects of its change on the objectives are reported in Figure 11.

Since the donor's reaction to time has an exponential effect on attractiveness, a decrease and an increase in the donor's sensitivity to waiting time, respectively, reduce and increase the attractiveness of the centers, the amount of blood donation, and, ultimately, the total costs of the network. The changes in both cases are significant.

7. The Managerial and Practical Implications

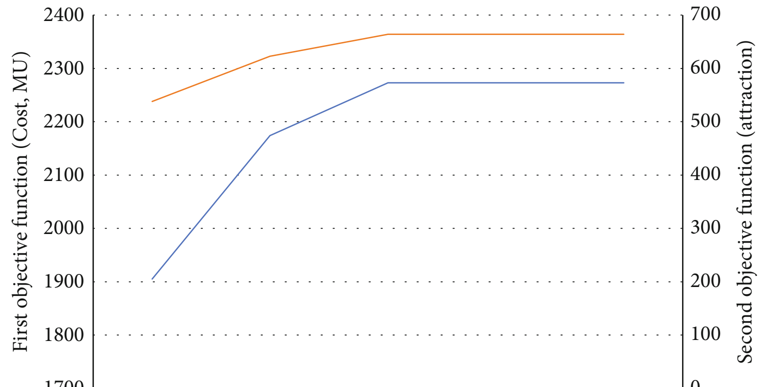
In general, the main managerial-practical insights can be concluded as follows:

(i) The performance and attractiveness of a BSC can be enhanced significantly if the number of the collection centers and the amount of blood sent from the receiving centers to the demand nodes are increased

(ii) On the other hand, as the dimensions of the problem grow, especially the number of blood products, the solution time of the proposed mathematical formulation increases

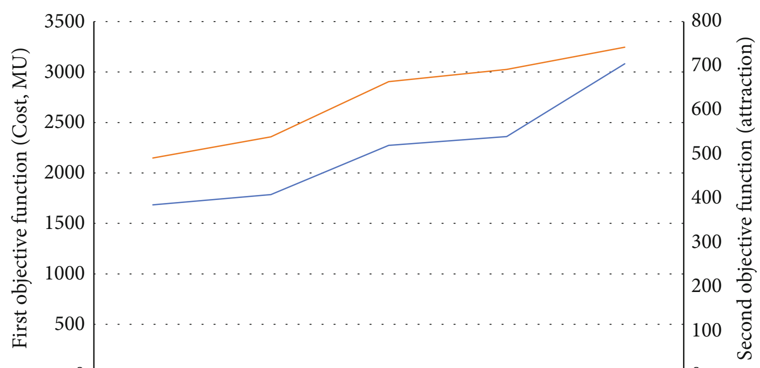
(iii) As the attractiveness grows, the fixed and operating costs of the blood supply chain also increase. This clearly represents the conflict between the two objective functions and emphasizes the necessity of establishing a reasonable balance between the level of attractiveness and costs. Accordingly, the influential decision-makers of the supply chain should choose the attractiveness and cost of the chain (one of the Pareto points) with a smart look and consider all hidden and visible aspects

(iv) Based on the proposed Pareto diagram, choosing an equilibrium point between two objective



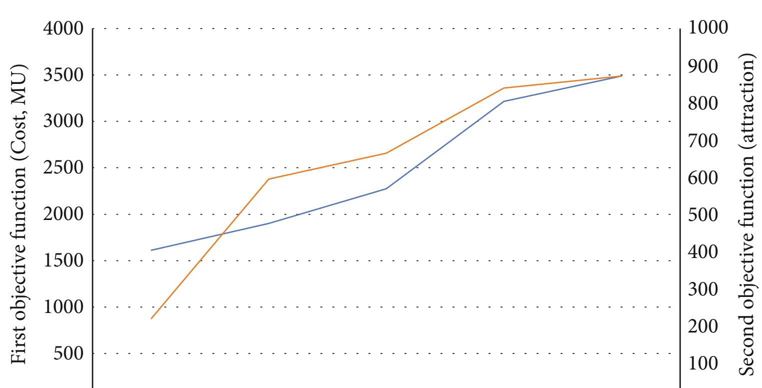
	−20%	−10%	0	10%	20%
First Obj	1905	2174	2273	2273	2273
Second Obj	538	623	664	664	664

FIGURE 5: Sensitivity analysis of a set of blood facility parameters ($Sa_{lp_1 t}$, Sb_{pt}, Sc_{rpat}, Se_{rpat}, Sk_{hpat}).



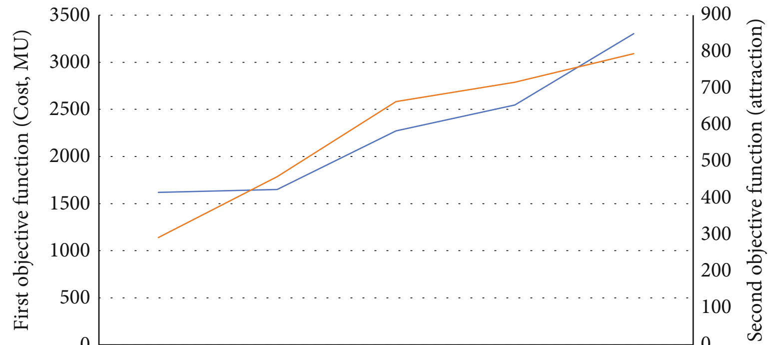
	−20%	−10%	0	10%	20%
First Obj	1684	1787	2273	2360	3082
Second Obj	491	539	664	692	742

FIGURE 6: Sensitivity analysis of the advertisement parameter (σ_w).



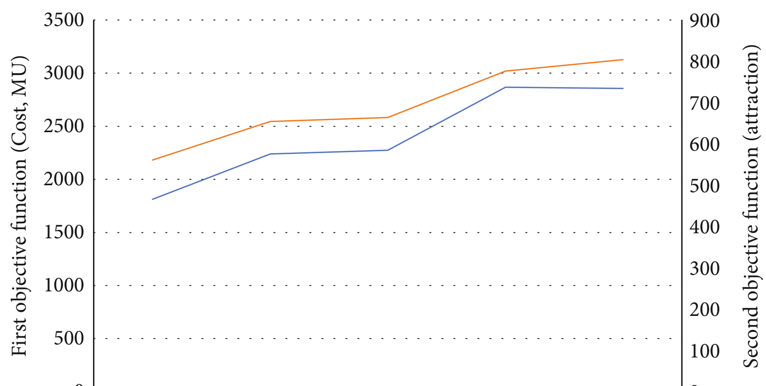
	−20%	−10%	0	10%	20%
First Obj	1612	1902	2273	3214	3488
Second Obj	219	595	664	840	872

FIGURE 7: Sensitivity analysis of the advertising impact parameter ($S\sigma_w$).



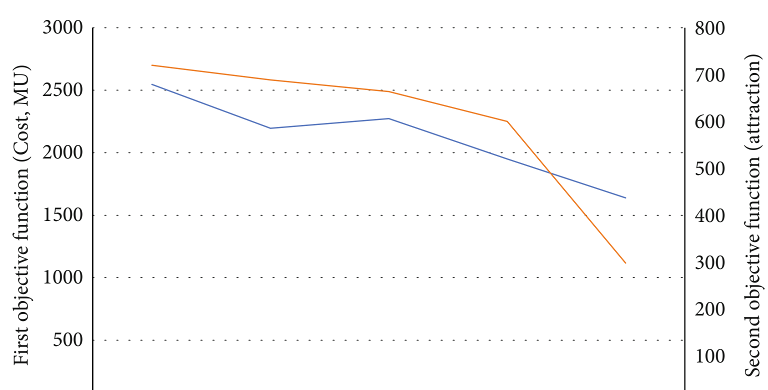
	−20%	−10%	0	10%	20%
First Obj	1619	1650	2273	2547	3304
Second Obj	293	459	664	717	795

FIGURE 8: Sensitivity analysis of the experience parameter (ϑ_w).



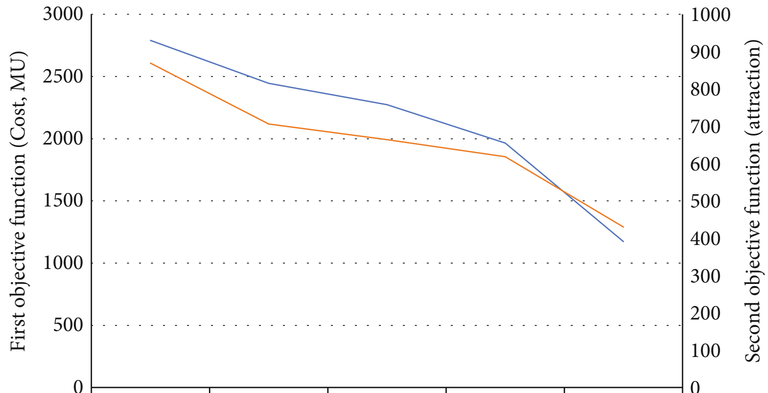
	−20%	−10%	0	10%	20%
First Obj	1812	2240	2273	2867	2856
Second Obj	561	654	664	776	804

FIGURE 9: Sensitivity analysis of the impacts of reputation and work experience ($S\vartheta_w$).



	−20%	−10%	0	10%	20%
First Obj	2547	2197	2273	1949	1639
Second Obj	720	689	664	600	298

FIGURE 10: Sensitivity analysis of the time spent on donating blood (τ_w).



	−20%	−10%	0	10%	20%
First Obj	2790	2444	2273	1964	1173
Second Obj	869	706	664	618	430

Figure 11: Analysis of the donor's sensitivity to time ($S\tau_w$).

functions is not difficult and improves the overall utility of the supply chain to a significant extent

(v) Growing the capacity of mobile facilities up to a certain amount (for example, up to 20% of the original capacity) can lead to a growth in the attractiveness of donating blood, and spending more in this field will not improve the attractiveness

(vi) By growing the cost of advertising, the attractiveness of blood donation centers increases, and blood donation increases. On the other hand, by not spending money on advertising, the number of people who come to donate blood will be reduced, and subsequently, the operational costs will be reduced. Of course, it should be mentioned that in the COVID-19 conditions, the reduction of operating costs is not much considered, and the most important item is the reduction of the number of deaths

(vii) The role of the experience and expertise of the employees of different blood donation centers cannot be ignored and can have a significant impact on the attractiveness of the centers and the blood donation process

(viii) In the COVID-19 conditions, because of infectious diseases, it is very critical for blood donors not to be delayed in blood donation centers and to donate blood quickly. Therefore, there is a very significant relationship between the reduction of blood donation time and the attractiveness of the centers and, accordingly, the amount of blood donated

The aspect of the generalizability of the present study compared to other similar blood supply chains around the world is that the proposed approach can be used in an efficient and generalizable way in blood transfusion organizations of different countries in the world. The level of attractiveness in the second objective function is one of the most important and vital decision variables, which is determined by the proposed mathematical model depending on the input parameters and conditions of each country. It depends on parameters such as types of transportation operating costs, capacity of facilities and mobile centers, distance between centers, maximum coverage radius, procurement costs, advertising budget, staff experience, and donor sensitivity. Accordingly, all the mentioned parameters have been comprehensively included in the proposed mathematical modeling so that the generalizability aspect of the present study can be adequately met in relation to other similar blood supply chains around the world.

8. Conclusions and Future Works

This study focused on a multilevel supply chain for blood products during the COVID-19 pandemic. The model developed for this chain determines the location of new regional, local, and mobile centers as well as the means of transporting blood products. A review of the research literature emphasizes that only a few studies have dealt with blood supply and distribution chains, and they have ignored the relationship between centers and transportation facilities, which plays a significant role in the efficiency of a BSC. Moreover, the critical "attractiveness" aspect of the blood supply chain has not been considered. Therefore, the present study undertook the cost reduction and attractiveness improvement of supply chains for blood and its products in COVID-19 conditions as probably the most important criteria of efficiency. To this end, the best locations were selected to establish new blood centers along with mobile units where the apheresis method could be practiced. The model was also designed to meet the attractiveness requirement of the blood donation centers and the demands for plasma. In this regard, an objective function defined on the basis of sensitivity analyses accounts for the reduction of donation waiting time, increase of facility capacity, advertising, and the reputation and work experience of centers. Implementing educational and promotional intervention programs such as explaining the benefits of blood donation and establishing a donor recruitment campaign can have positive effects on the increase of blood donation. This is why the model places an emphasis on the maximization of the attractiveness of blood centers. As for the general performance of the BSC, the decision variables are optimally controlled, and the loss and shortage of blood plasma are minimized. The results show that the performance and attractiveness of a BSC can be enhanced significantly if the number of the collection centers and the amount of blood sent from the receiving centers to the demand nodes are increased. On the other hand, as the dimensions of the problem increase, especially the number of blood products, the solution time of the proposed mathematical model grows. Other managerial conclusions and practical implications are represented in section 7.

The following recommendations may be taken for future research:

(i) Considering the issues of blood products' longevity and supply chain reliability

(ii) Using innovative and metaheuristic solution algorithms due to the growth of problem dimensions which leads to increased solution time

(iii) Applying simulation methods such as multifactor systems for the practical planning of BSC networks

(iv) Extending the model by combining inventory routing transportation problems: it can include various objectives about such issues as reliability and blood delivery time as well as heuristic and metaheuristic solutions for large samples to deal with the complexity of the formulation implementation. Accordingly, the reduction of disruption in the working and transportation times of blood collection centers can be measured

(v) In order to grow the attractiveness of blood centers, the following points are recommended for model development:

  (a) Planning and implementing a management system for blood donation along with the use of information technology to gain quick access to blood donor records and to find blood donors needed in emergencies. This may be fulfilled through (a) using a system to inform and promote blood donation programs via social and other media, (b) maintaining the records of donors and their blood profiles for effective donor performance and blood management in blood banks, and (c) promoting advertisements through social media to provide services to blood donors and recipients.

  (b) Designing a model to estimate the donor population so as to manage blood collection better

  (c) Establishing incentive mechanisms for blood donation according to the type of donors (primary blood donors and frequent donors)

Notations

Sets and Indices

$I = I' \cup I''$: Set of regular donors and those having recovered from coronary heart disease $(i', i'' \in I)$

M: Set of candidate locations for mobile facilities $(m \in M)$

L: Set of candidate locations for local blood centers $(l \in L)$

R: Set of candidate locations for regional blood centers $(r \in R)$

$M \cup L \cup R = W$: The whole set of centers responsive to donors $(w \in W)$

$P_1 \cup P_2 \cup P_3 \cup P_4 \cup P_5 = P$: Whole blood (P_1), red blood cells (P_2), platelets (P_3), plasma type (I) (belonging to normal people) (P_4), and type (II) plasma (belonging to people having recovered from coronary heart disease) (P_5) $(P_i \in P)$

$k_1 \cup k_2 \cup k_3 = k$: Set of lifetimes of whole blood products, red blood cells, and platelets $(k \in K)$ (by day)

H: Set of demand points $(h \in H)$

$A = A' \cup A''$: Set of simple blood collection and apheresis methods $(a', a'' \in A)$

T: Set of periods $(t \in T)$

S: Set of the COVID-19 pandemic status scenarios $(s \in S)$.

Parameters

Fa_l: The cost of setting up local blood center l

Fb_r: The cost of setting up regional blood center r

$\mathrm{Fc}_{m'm''t}$: The cost of moving each mobile device from place m' to place m'' during t

Ta_{pt}: The cost of transporting each unit of blood product p per kilometer per t

Oa_{ipt}: The cost of collecting each unit of blood product p from donor group i during t

Pa_{pt}: The cost of production per unit of blood product p in regional blood centers in t

Hc_{pt}: The cost of maintaining each unit of blood product p during period t

Sa_{lp_1t}: Local blood center capacity l to collect whole blood (p_1) during period t

Sb_{pt}: The capacity of mobile facilities to collect blood products p during t

Sc_{rpat}: The capacity of regional center r to collect and produce blood products p obtained by collection method a during period t

Se_{rpat}: The capacity of regional center r to store blood products p obtained by collection method a during period t

Sk_{hpat}: Demand point capacity h to store blood products p obtained by collection method a during period t

Da_{im}: The amount of route between donor group i and facility m
$Db_{i'l}$: The amount of route between donor group i' and local center l
Dc_{ir}: The amount of route between donor group i and regional center r
Dd_{mr}: The amount of route between facility m and regional center r
De_{lr}: The amount of route between local center l and regional center r
Dh_{rh}: The amount of route between regional center r and demand point h
Ra_m: Maximum coverage radius of mobile facility m to serve donors
Rb_l: Maximum coverage radius of local center l to serve donors
Rc_r: Maximum coverage radius of regional center r to serve donors
Po_p: Percentage of blood product production p
Ea_{hpat}: Expiry cost per unit of extra blood product p obtained by collection method a at the demand point h during t
Dm^s_{hpat}: Hospital demand h for blood products p obtained by collection method a during t under scenario s
τ_w: Time spent on the blood donation process at blood center w
σ_w: Advertising budget in blood center w
ϑ_w: Experience factor in blood center w
$S\tau_w$: Donor sensitivity to time τ_w
$S\sigma_w$: Donor sensitivity to advertising σ_w
$S\vartheta_w$: Donor sensitivity to experience factor ϑ_w
Dr^s: Average donation rate under scenario s
Pop_w: The population of the area allocated to blood center w
Ub_w: The best productivity available in blood center w
π^s: Probability of scenario s
φ: A very large number
ε: A number from zero to one.

Decision Variables

YL_l: If local blood center l is launched, 1; otherwise, 0
YR_r: If the center of region r is set up, 1; otherwise, 0
ZA^s_{imt}: If donor group i is allocated by mobile facility m in period t under scenario s, 1; otherwise, 0
$ZB^s_{i'lt}$: If donor group i' is allocated to local center l in period t under scenario s, 1; otherwise, 0
ZC^s_{irt}: If donor group i is allocated to regional center r during period t under scenario s, 1; otherwise, 0
$MV^s_{m'm''t}$: If the mobile facility passes from place m' to m'' in interval t under scenario s, 1; otherwise, 0
XA^s_{impt}: The amount of blood product p donated by donor group i on mobile device m during t under scenario s
$XB^s_{i'lp_1t}$: The amount of whole blood p_1 donated by donor group i' at local center l during t under scenario s
XC^s_{irpt}: The amount of whole blood p donated by donor group i in regional center r during t under scenario s
XD^s_{mrpt}: The amount of whole blood p transferred by mobile facility m to regional blood center r during period t under scenario s
$XE^s_{lrp_1t}$: The amount of whole blood p_1 transferred from local center l to regional center r during t under scenario s
XG^s_{rhpakt}: The amount of blood product p obtained from collection method a with age k days posted by regional center r to the point of demand h during t under scenario s
XH^s_{rhpakt}: The amount of blood product p obtained from collection method a with age k day consumed at the point of demand h during t under scenario s
PR^s_{rpat}: The amount of blood product p produced by collection method a in regional center r during t under scenario s
SH^s_{hpat}: Deficiency of blood product p obtained from collection method a at the point of demand h during t under scenario s
EX^s_{hpat}: The amount of extra blood product p obtained from collection method a expired at the point of demand h during period t under scenario s
IR^s_{rpat}: Blood product inventory level p obtained from collection method a in regional center r during t under scenario s
IH^s_{hpakt}: Blood product inventory level p obtained from collection method a with age k days at the point of demand h during t under scenario s
AT^s_{wt}: The attractiveness of blood center w under scenario s during t.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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