An equity-oriented multi-objective inventory management model for blood banks considering the patient conditions: A real-life case

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Abstract. The absence of systematic disparities in health utilization leads to achieving equity in health. However, equity in delivering healthcare services is always challenging because of the financial and medical resource constraints. In this regard, a practical multi-objective mixed-integer linear programming model with priority-differentiated demand classes is presented for cost-effective inventory management of blood products considering the health equity. The system deals with multiple substitutable products. There are elective and non-elective demands, which are categorized into three main classes based on medical urgencies. The health objectives are investigated to achieve a desirable health equity level in delivering healthcare services to patients. Moreover, the economic objective is pursued to minimize the total costs incurred across managing the inventory without weakening the service level. An effective demand-oriented hybrid heuristic is proposed to issue and allocate blood for equitable demand satisfaction. In this regard, a goal programming approach is utilized to find an optimum solution. The applicability of the model is validated through a real case study. Finally, several sensitivity analyses are conducted to gain useful managerial insights. According to the results, the proposed model presents a proper solution by making a reasonable health-economic trade-off. The results also confirm a beneficial improvement in the patient care and promotion of health equity.

1. Introduction

Health equity is an essential criterion in the case of health services. Equity in health implies that healthcare systems should ideally provide a fair opportunity

for everyone to attain their full health potential [1]. In this regard, healthcare systems mainly focus on delivering the best quality of service for patients. However, the increasing population age, recent medical advances, more aggressive treatment of some diseases, and growing need for various types of medicines have made it challenging to provide the highest medical services and products required by the health system [2]. This issue can be very challenging because there are different ways to define equity, evaluate its effects, and group patients to analyze their health equity. Therefore, a definition is needed to be operationalized

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based on the measurable criteria [3]. With regard to healthcare systems, social equity entails that a patient be appropriately treated in different aspects of the disease. This requirement is consistent with a familiar distinction between the horizontal and vertical social equities [4]. In healthcare systems, horizontal social equity requires similar medical services for similar patients. On the contrary, vertical social equity entails dissimilar medical services for dissimilar patients in terms of Urgent Levels (ULs) and commensurate with their illness [5].

Healthcare supply chain management may be considered more complex than the typical industrial applications such as food supply chain. In healthcare, each product item may be considered crucial. In addition, there is a perceived need to supply very high service levels. There is, however, a high production value and, in many cases, a need for special handling to minimize expiration or spoilage. Hence, logistics and inventory management costs can be substantial [6]. In the meantime, controlling the inventory of the blood products, especially blood platelet, is much more difficult [7]. The main challenge here is a rare and limited blood supply, inadequate access to donors, highly limited shelf-lives, and regular use in treating certain diseases such as cancer [8]. These issues should be eliminated to provide a desirable health service to patients. Simultaneously, the least possible shortage and wastage can be desirably witnessed [9].

The healthcare administrators aim to provide demand-oriented services and make them accessible to different patient groups. They also seek to minimize the total system costs by adopting cost-efficient policies, followed by shortage reduction without any wastage or failure [10]. In this regard, the healthcare managers need to choose efficacious policies to serve the patients properly and keep the blood inventories at an optimum level. Implementing appropriate policies for the equitable assignment of health services in a way that minimizes health risks and operating costs is one of the main concerns of decision-makers [11,12].

Although meeting demand is of paramount importance, the operational cost of handling blood products cannot be ignored [8]. Due to the rapid growth in healthcare expenditure worldwide and simultaneous growth of demand for healthcare services, developing efficient and effective healthcare systems has become an essential concern for governments and healthcare managers [13]. An increase in the safety measures, new donor recruitment programs, a surge in demand for blood products, and inefficient usage of resources are cited as the possible reasons for this cost increase [14]. Thus, society must improve utilization within Blood Supply Chains (BSCs) and reduce costs to make the best use of limited blood resources [15].

Blood comprises several components such as Red Blood Cells (RBC), platelets, and plasma with different shelf-life and applications. Depending on the patient's condition, the whole blood or one of its components may be needed for treatment [16]. Moreover, there are a diversity of blood types in eight blood groups, namely ABO and Rh [17,18]. All blood types of a particular blood component have the same shelf-life. Usually, the patient's blood requirement is met with the same blood type. Note that blood substitution is only allowed among different blood types (not different components) based on the medical priorities and the physician's decision in case of shortage [16].

The focus point of successful BSC management is inventory control [19,20]. Inventory management is part of more extensive operations. It plays a supportive and active role in improving the overall logistics and supply chain performance. Utilization of streamlined inventory management techniques can significantly contribute to making the blood banking operations more efficient to a large extent. Even though inventory management systems use cost-based models, hospitals need to focus on the patient service level. Availability of the healthcare items of high quality in a continuously fluctuating environment is challenging [15].

In this regard, a systematic inventory management approach and timely use of medical products before their expiration date can dramatically help the healthcare system spend financial resources more economically through removing redundant costs without lowering the level of offered healthcare services [20]. The current study aims to find a proper solution for the decision-makers by proposing a health-economic inventory management model.

In this paper, a replenishment policy for inventory management of blood banks is studied. In addition, an issuance and allocation rule based on the current practices on substitutable and perishable products is proposed. In doing so, an effective heuristic policy can be developed to generate further insights into the general problem. Moreover, the health-economic challenges of blood banks are elaborately discussed in this study. In this respect, two main objectives are pursued: first, health equity in delivering blood products to different patient groups; second, the optimal management of blood products to minimize the risks of lives and economic costs.

This paper seeks to answer the following questions: What strategies should be adopted to minimize the outdated blood units without facing any shortages? How much of a specific blood product and in which planning periods should it be replenished? Which demand should be met first to observe the health equity and the desired level of medical services on the one hand, and the least amount of shortage on the other hand? How does the system deal with

the real-world environment challenges and emergency demands that pose the least risk to the patients' lives? How is an inventory issued from the blood bank and allocated to demand so that the least amount of wastage occurs?

The rest of this paper is organized as follows: Section 2 reviews the related literature. Sections 3 and 4 discuss the applied methodology and proposed mathematical model, respectively. Section 5 investigates a real case study, including the solutions, obtained results, and discussion over the findings; sensitivity analyses are conducted on some of the critical parameters. Finally, Section 6 presents the conclusion and future streams.

2. Literature review

A review of the most related papers in blood inventory management and health equity literature is conducted in this section. Further, the research gap and main contributions of the current study are mentioned. A summary of the recently published papers on the related topics is provided in Table 1 and discussed in the following.

2.1. Related works

In this section, the most related papers are studied in terms of problem domains, modeling, and solution methods. There is an extensive body of research on BSC. Most research studies in this field have mainly focused on minimizing the inventory costs, shortage, and wastage using different modeling tools and techniques to increase both efficiency and effectiveness of the overall BSC management [20,21]. In this regard, replenishment policies are used to determine the optimal ordering quantity and replenishment periods. In this regard, different studies considered classical or modified periodic review [9,22,23] and continuous review [24,25] policies. Considering the lead-time as zero or constant is a logical and common approximation for modeling such healthcare systems [26–28].

In addition to the replenishment policy, the issuance policy also affects the inventory shortage and wastage [29]. The two policies of First-In-First-Out (FIFO) for the consumption of older products [26,30] and Last-In-First-Out (LIFO) for the consumption of fresher ones [30] had the highest applicability in the literature. In addition, some studies suggested modified [29], hybrid, and heuristic policies [9]. Ideally, it is suggested to consume older products earlier to avoid their wastage, but this is not always possible. For blood products, the issuance policy may change depending on the medical preferences and patient conditions. This matter results in sorting out the demands for a given product according to their required age (or remained shelf-life) and order of meeting [26].

As Table 1 suggests, single or multiple objectives are considered in the literature. The modeling methods can be categorized into the mathematical programming, simulation, and other methods. The mathematical programming methods mainly consist of Mixed-Integer Linear Programming (MILP) and Mixed-Integer Nonlinear Programming (MINLP) models. Studies that developed mathematical modeling, in most cases, use exacts, heuristics, and metaheuristic solution approaches [31]. Most extended mathematical models in blood inventory management were implemented in a deterministic environment because of the complexity of coping with uncertainty [32]. However, more attention has been paid to BSC uncertainties in the last two decades. In general, three types of uncertain environments namely stochastic, fuzzy, and robust were defined. In this regard, different or hybrid approaches were used to model them [2].

The importance of blood freshness for some treatments was highlighted in many studies [8,16,26]. For example, platelet demand from organ transplant patients is treated as an emergency including receiving the youngest possible blood platelets. Oncology patients request the youngest platelets, and traumatology patients have no preference concerning the blood platelet's age [33]. In addition, transfusion of the eldest RBC impacts short- and long-term survival rates for cardiac patients [8].

In summary, certain patients require the freshest available platelets to minimize complications during treatment. In contrast, the risk of complication for other patients is believed to be minimal. This paper proposes a model with an age-differentiated demand to reflect findings in the literature and the current practice in blood management, as well. In this case, the classical FIFO and LIFO policies may not necessarily be appropriate to meet the patients' demands. Therefore, it is better to consider age-based issuance policies to manage perishable inventories. In this regard, First-Expired-First-Out (FEFO) and Last-Expired-First-Out (LEFO) policies are suggested [8,34].

Inventory control systems are recommended to be aligned with the patient's condition. Technically and scientifically, demand for healthcare items is closely linked to the physician recommendations based on the patient conditions [13]. In healthcare systems, patient conditions are divided into three categories based on urgency: immediate/severe, moderate/delayed, and minor [10]. In BSC, a specific product can be prescribed to treat diseases in different urgent classes [8,10]. The demand is classified based on the age of the requested blood product in some previous works [8,16,26]. However, to the authors' knowledge, no relevant studies have been conducted on demand classification based on medical urgencies in the field of blood inventory management.

Table 1. Summary of the most related papers in the field of inventory management of medical products in recent publications.

Authors	No. of products	Obj.	Ordering policy	Issuing policy	Model. approach	Solution method	Demand differentiations	Capacity constraints	Substitution	Emergency condition	Expedited orders	Equity	Case study
Rajendran & Ravindran (2017) [26]	SP	SO	(s,S),BaS,MBS,WMV,LVM	FIFO	MILP	H	–	–	–	–	*	–	N
Dillon et al. (2017) [22]	MP	SO	(R,S)	–	MILP	EX	–	–	*	–	*	–	Y
Dehghani and Abbasi (2018) [24]	SP	SO	(S-1,S)	FIFO	NLP	H	–	–	–	–	*	–	Y
Hosseinifard and Abbasi (2018) [28]	SP	SO	(S-1,S)	FIFO	MILP	EX	–	St	–	–	–	–	N
Osorio et al. (2018) [41]	MP	MO	OP	–	MILP	H	–	S	–	–	–	–	Y
Sarhangian et al. (2018) [42]	SP	SO	OP	FIFO	NLP	SIM	–	–	–	–	–	–	N
Samani and Hosseini-Motlagh (2019) [43]	MP	MO	OP	–	MILP	EX	–	S,St	–	–	–	–	Y
Uthayakumar and Karuppasamy (2019)[44]	SP	SO	EOQ	–	NLP	AT	–	–	–	–	–	–	Y
Paul et al. (2019) [45]	SP	SO	OP	–	MILP	EX	–	–	–	–	*	–	N
Ezugwu et al. (2019) [19]	MP	SO	OP	FIFO	MILP	MH	–	–	–	–	–	–	N
Ezugwu et al. (2019) [19]	MP	SO	OP	FIFO	MILP	MH	–	–	–	–	–	–	N
Rajendran & Ravindran (2019) [20]	SP	SO	(s,S,α,Q)	FIFO	MILP	MH	–	–	–	–	*	–	Y
Larimi et al. (2019) [17]	MP	MO	OP	FIFO	MILP	EX	SL	S,St	–	–	–	–	Y
Srinivas & Rajendran (2019) [46]	SP	SO	(s,S,β,Q)	FEFO	MILP	EX	–	–	–	–	*	–	N
Hosseini-Motlagh et al. (2020) [18]	MP	SO	OP	FIFO	MILP	EX	–	S,St	–	–	–	–	Y
Hosseini-Motlagh et al. (2020) [32]	MP	MO	OP	FIFO	MILP	EX	–	S,St	*	–	–	–	Y
Attari & Abdoli (2020) [47]	MP	SO	OP	FIFO	MINLP	EX	–	S	*	–	–	–	Y
Derikvand et al. (2020) [9]	MP	MO	OP	Mixed FIFO &LIFO	MILP	SIM	SL	S,St	–	*	–	–	Y
Current research	MP	MO	OP	H	MILP	EX	SL,UL,SA,AP	S,St	*	*	*	*	Y

Note: SP: Single Product; MP: Multi Products; SO: Single Objective; MO: Multi Objectives; AP: Assignment Policy; NLP: Nonlinear Programming; MILP: Mixed Integer; Linear Programming; EX: Exact; H: Heuristic; MH: Metaheuristic; SIM: Simulation; SL: Shelf Life; UL: Urgent Level; SA: Substitution Allowance; MDP: Markov Decision Process; FEFO: First-Expire-First-Out; FIFO: First-In-First-Out; LIFO: Last-In-First-out; OP: Optimal Policy; EOQ: Economic Order Quantity; DP: Dynamic Programming; Y: Yes; N: No; St: Storage; S: Supply.

Based on the reports of a recent study on a real blood bank process, the blood demands are generally divided into two main categories in terms of election administration: elective (scheduled) and non-elective (non-scheduled) [35]. However, hospitals mostly encounter non-elective demands in case of emergencies. The non-elective demands mainly arise in emergency rooms, intensive care units, and operating rooms [13]. The current practice of hospitals is to delay the elective surgeries when the inventory on hand is limited [8]. In the literature, the emergency condition has often been overlooked. Some of the previous studies referred to the emergency as an instance of shortage in the system. In this case, the required inventory is met through an emergency or expedited order [20,31]. The emergency demands are typically less than the scheduled ones. Note that the emergency demand might occur among elective and/or non-elective demands. This kind of shortage can hurt the blood bank's reputation; therefore, more optimization must be done to prepare for emergency conditions [9].

Given the diversity of blood types (ABO), physicians prefer using the same blood type for patients in the first place. Nevertheless, in case of shortage, substitution is a possibility based on medical priorities [35]. Most previous models are generally limited to one or two non-substitutable products for more simplification [8,20,26]. However, in recent years, the substitution possibility among blood types has received much more attention than ever [16].

Several papers put their primary focus on the blood management at multiple locations with possible transshipment options. In this case, a lateral transshipment policy is taken into account [28]. In practice, there is no trading of blood platelets between different blood banks (due to the high perishability of the platelets). However, hospitals can get fresher platelets from other blood centers or hospitals in case of shortage, especially in emergencies. In this case, an expedited replenishment takes place [33]. The same assumption is made in this paper to get closer to real-life conditions. Note that technically, this assumption is no different from assuming "lost demand" in inventory management. The excess demand does not impact either the inventory composition or usage in future periods. However, a penalty cost is incurred for each unit of demand that cannot be satisfied immediately from inventory on hand [8].

Some researchers defined equity in health as an essential criterion for services and level of access to public health services [10]. Using a supply-demand framework, they discussed the key challenges in achieving a health system that provides equity in service delivery, health financing, and financial risk protection. Heretofore, many healthcare researchers have conceptually described social equity for medical services [1,4,5]. Due to the hierarchical complexity of health equity, few healthcare researchers have incorporated health equity and patients' medical priorities in their quantitative studies so far [36].

A review of the existing literature shows that a majority of the previous studies in this area are qualitative. To the best of the authors' knowledge, few papers have pragmatically focused on the social equity implementation, considering the operational research approaches to optimizing healthcare performance. In recent work, the social equity of the BSC was considered for three types of injuries differentiated in terms of the medical ULs and demand satisfaction preferences [10]. In another research in this field, to make an equitable health service network redesign, equity is calculated by the most urgent need of a patient from a medical viewpoint and transportation time from the logistics viewpoint [2]. To the best of the authors' knowledge, the blood inventory management model considering health equity has not been formulated so far.

2.2. Research gap and contributions

Blood inventory optimization is a critical point for blood services mainly because expenditures must be strictly controlled while maintaining high medical service levels. This paper is motivated to examine the health-economic optimization of blood inventories when a hospital blood bank is responsible for blood purchases and logistics to internal wards.

This study adds further credibility to the importance of applying a practical approach to optimally manage the blood inventories by developing an equity-oriented demand-oriented mathematical model for healthcare systems. The elective and non-elective demands are considered and classified into three classes in terms of emergencies. The product freshness, substitution allowance, response urgency, and allocation policy are determined, considering the conditions of each patient group and current practice of the blood bank. The authors practically investigated the problem under study as well as the assumptions in a previous study related to the blood banks process mode of real hospitals [35].

To the best of the authors' knowledge, this paper is the first pragmatic study that addresses health equity in blood inventory management as one of the main criteria involved in satisfying the surging demands. Altogether, this paper aims to fill the literature gap; hence, it can be differentiated from the previous blood inventory management studies by bringing together the following main contributions:

- Employing health equity in blood inventory management for the first time to provide a desirable level of accessibility of medical services for all patient groups based on their medical priorities;

- Making a trade-off between the equity and economic objectives of healthcare systems;

- Considering elective and non-elective demands and dividing them into three priority classes based on the blood age, substitution allowance, medical urgency, and allocation policy;

- Adopting a practical policy to meet the emergency demands;

- Implementing a hybrid heuristic policy to issue and assign the blood inventory so that the least shortage and wastage can be ensured;

- Addressing a practical perspective for the planning of a multi-product inventory management system with substitution allowance, limited supply resources, and storage capacity constraint over a multi-period horizon;

- Applying a real-life case to demonstrate wide practicality of the proposed problem in healthcare systems.

3. Methodology

The proposed model in this research is a Multi-Objective Mixed-Integer Linear Programming (MOMILP) model. The objectives should be satisfied efficiently in a non-dominance space by finding global Pareto optimal solutions. In the first step, a mathematical model is proposed. Then, an extended Goal Programming (GP) approach is employed to solve it in an actual situation. Next, the GP approach is used for making a trade-off among different objectives of the proposed model.

Different approaches have been proposed in the literature to solve the bi- or Multi-Objective Decision-Making (MODM) optimization problems. The methods are applied for combining the objective functions into only one. GP is an old yet applicable solution method among the available ones. This approach is used when the number of objectives is too many, while their importance is mostly the same [37]. It is selected to solve our multi-objective inventory management problem due to its close relation with linear programming [38]. Minimizing shortage as well as inventory level, substitution, non-freshness, non-response to non-elective demand, and total system costs are the main objectives this problem pursues. Naturally, some goals may contradict others whose associate weights determine their importance. When decision-makers can easily determine the weight of each goal, the GP approach seems appropriate [38]. This is the reason why the GP approach is selected.

A goal is first defined for every objective, ranging between 0 and 1, to implement the GP approach.

The objective function is to minimize the maximum deviation from each goal. Generally, a typical MODM problem is defined as follows [39]:

$$\begin{cases} \min\left(f_1\left(x\right), f_2\left(x\right), \ldots, f_n\left(x\right)\right) \\ x \in X \end{cases} \tag{1}$$

The optimal value of each objective is shown by f_i^*, where $i = 1, 2, \cdots, n$. In real-world MODM problems, the conflict among objectives is taken into account and consequently, there is no solution $x^* \in X$ for which all objectives are optimized. Accordingly, if we assume that A is a solution method and x^A is its output, this solution approach is more efficient when $f_i\left(x^A\right)$ has less distance from f_i^*.

In the GP approach, an acceptable value is first considered for every objective (e.g., its optimal value f_i^*). Then, the goal function is defined so that followed by any reduction in the objective function, the goal value will linearly increase. Suppose that $m_i = f_i^*$ is the minimum/ideal value of the ith objective and M_i its upper bound. As a result, in the GP method, the ith objective can be defined as follows [38]:

$$G_i\left(x\right) = G\left(f_i\left(x\right)\right)$$

$$= \begin{cases} 0; & f_i\left(x\right) \geq M_i \dfrac{M_i - f_i\left(x\right)}{M_i - m_i} & x \in X \\ 1; & f_i\left(x\right) \leq m_i \end{cases} \tag{2}$$

Then, based on the GP method, MODM problems could be stated in terms of a single-objective model, as shown below:

$$\begin{cases} \max z = \min\left\{G_i(x) : i = 1 : n\right\} \\ G_i(x) = \dfrac{M_i - f_i(x)}{M_i - m_i}; & i = 1, 2, \ldots, n \\ x \in X \end{cases} \tag{3}$$

where if $f_i\left(x\right) \rightarrow m_i$, then, $G_i\left(x\right) \rightarrow 1$.

In some cases, instead of the formulation mentioned above, the *minimax* technique is used. This technique is employed in this research as well. In the *minimax* method, the maximum deviation from the optimal value of the objectives is minimized. The formulation of the *minimax* method could be stated as follows [40]:

$$\begin{cases} GP \\ \min L_\infty(d_i(x), & i = 1, 2, \ldots, n) \\ d_i(x) = \dfrac{f_i(x) - m_i}{M_i - m_i}; & i = 1, 2, \ldots, n \\ x \in X \end{cases} \tag{4}$$

where L_∞ signifies the extreme norm, and $d_i\left(x\right) = \dfrac{f_i(x) - m_i}{M_i - m_i}$ the relative deviation of each objective function from its optimal value. The formulation mentioned above could be linearized as follows [40]:

$$\begin{cases} GP \\ \min Z \\ Z \geq \frac{f_i(x) - m_i}{M_i - m_i}; \quad i = 1, 2, \ldots, n \\ x \in X \end{cases} \quad (5)$$

4. Problem statement and mathematical modeling

This study is designed according to the current concerns of a typical blood bank [35]. The proposed system aims to provide efficient equity-oriented strategies for blood banks [12]. Accordingly, considering the importance of human lives, healthcare systems mainly deal with health equity concerns in service delivery to ensure that the most negligible health risks happen. The current investigation seeks to find optimal ways to meet the blood demands economically with minimal shortage and wastage. The problem statement is presented in the following.

4.1. Problem statement
In this research, the demands are divided into two general groups, namely the elective and non-elective demands. Elective demands are scheduled based on the previous physicians' requests, while non-elective demands are unscheduled ones. The demands are also classified into three priorities based on the medical urgency classes at the physician's discretion and considering the social equity namely "High", "Moderate", and "Low" (i.e., high-priority to low-priority demands). The patients at each class have a specific medical condition and treatment urgency. Both elective and non-elective demands can fall into any of the above three classes. Figure 1 briefly illustrates the class specifications of the demands.

The product items in their first half-life are considered fresh. Those items that have passed their first half-life are considered ordinary (regular) in terms of freshness. At the end of the shelf-life of a product item, it is considered expired and discarded. The demands are periodical (daily) and independent. Figure 2 indicates the blood inventory flow in the proposed system [35].

The demand classes are differentiated by UL, substitution allowance, freshness value, and allocation policy. Equity-oriented treatment prioritizes demand satisfaction, not the same way as in the differentiated demands class. In this regard, a hybrid heuristic policy is presented for demand satisfaction. Suppose that the demand for a given product cannot be satisfied with the same product type due to shortage. In this case, one may consider a shortage-based substitution policy according to the patient's UL or use expedited service for immediate replenishment.

In the case of the expedited replenishment, a penalty is imposed on the system. After implementing the extended allocation and issuance hybrid policies, if some parts of demands have not yet been met, they would be lost. The supply is capacitated and provided only by one leading supplier. In addition, the products received from the supplier have a specific shelf life span. The statements on how to meet the demand for different levels of urgency are given in the following:

- *Class 1*: The highest priority demand is only for the freshest items to avoid medical risk. The same item could only meet the product demand at this level; hence, substitution in this UL is not allowed. It then would be lost and ordered immediately by imposing an expedited service penalty cost in case of shortage. An appropriate issuance policy, called the LEFO, is considered for this UL to assign the freshest items to the demand;
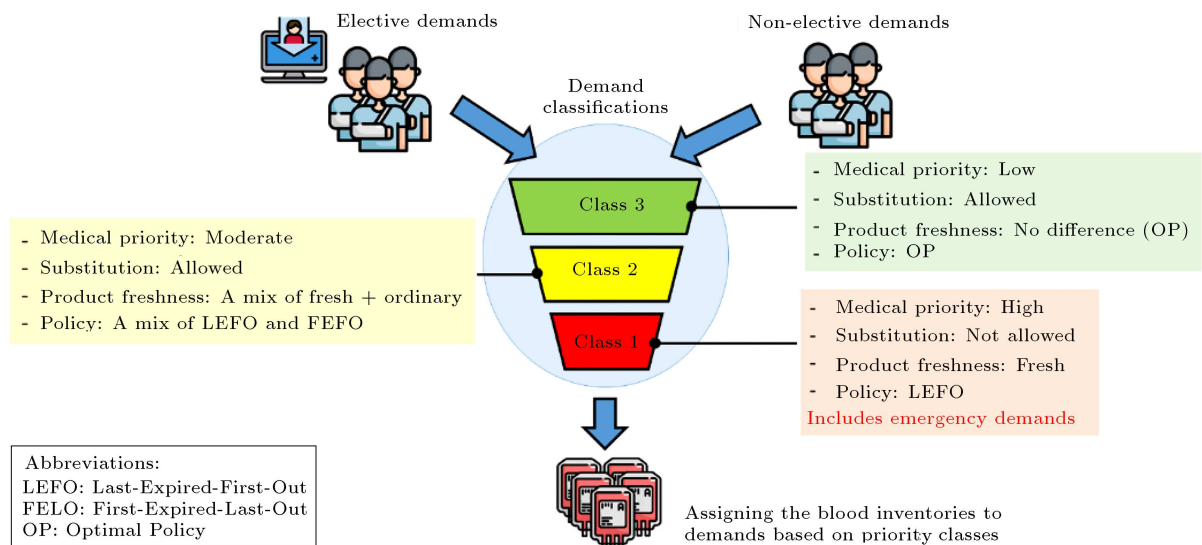

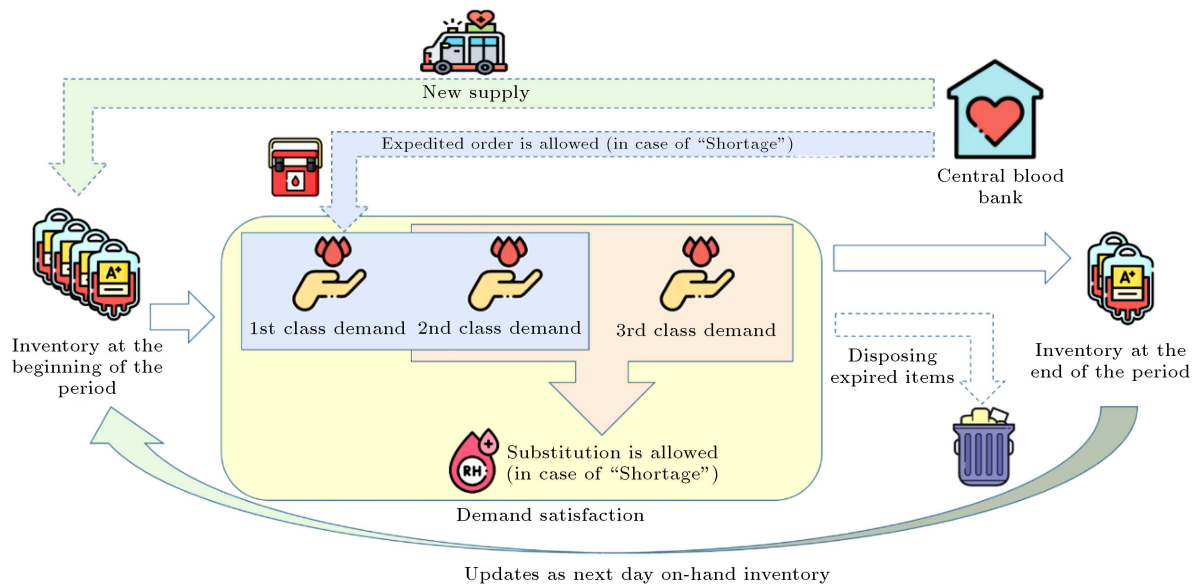**Figure 1.** Specifications of demand classes.

Figure 2. The inventory flows in the proposed system.

- *Class 2*: The moderate priority demand has lower medical sensitivity than Class 1; however, there are still some medical risks. In this regard, similar to Class 1, this level belongs to the fresh items, but it follows a different pattern. The issuance policy of demands satisfaction in Class 2 is a mix of FEFO and LEFO policies. First, the demand is met with fresh items in descending order. In this case, the FEFO issuance policy is used for demand satisfaction. According to the medical priorities, shortage-based substitution with the freshest items of other types of products is allowed at this level and it follows the LEFO issuance policy. If there is still some unmet demand after the substitution, it will be lost and ordered immediately through imposing expedited service penalty costs;

- *Class 3*: The lowest priority demand encounters the least level of health risk and medical sensitivity. Therefore, the remaining shelf-life of the products is not that important for demand satisfaction; however, it is preferred to use fresher ones to treat patients. Suppose that some parts of demands could not be met. In this case, shortage-based substitution with other types of products is allowed according to the medical priorities. If some demand parts are still unsatisfied, the shortage will be lost. In this case, Optimal Policy (OP) on issuance should be taken into account;

4.1.1. Assumptions

The following assumptions have been taken into account in this investigation:

- The planning horizon is finite and includes some specific periods (e.g., one-month plan with daily periods);

- The supplier capacity is limited and variable in each period;

- The demand for each product varies in each period;

- The shelf-life of all products is the same;

- The products are received in the freshest form from the supplier;

- The storage capacity of the medical system is limited and a maximum holding capacity is already determined for each product;

- The allowed ordering periods are already specified that are a subset of the planning horizon periods;

- The demand back-order is not allowed and the demand in each period must be satisfied in the same period rather than in the next one.

- The products at their first half-life are considered fresh and ordinary in their second half-life;

- Medical experts determine the importance of product availability for each UL in the range of 5 to 10 (number 10 is the most important);

- The substitution rate for the products ranges between 0 and 1, which is determined by medical experts. Here, 1 signifies fully compatible state, while 0 means a non-compatible one;

- The freshness importance of each product in each UL ranges from 5 to 10 and is determined by medical experts (number 10 is the most important);

- The lead-time to receive the order from the supplier is deterministic (one period). In addition, the expedited orders are received immediately in the same period from the supplier;

- The initial inventory of the system is negligible.

4.1.2. Notations

The notations and symbols used in the proposed mathematical model are listed in the following. Next, the mathematical formulation is presented.

Sets and indices

T Set of planning periods (day), $T = \{1, 2, \ldots, t, \ldots, |T|\}$

R Allowed replenishment periods (day), $R \subseteq T$

P Set of product types, $P = \{1, 2, \ldots, p, \ldots, |P|\}$

U Set of demand priorities (demand classes), $U = \{1, 2, \ldots, u, \ldots, |U|\}$

$S^{pp'}$ Set of substitutable products; product p can be substituted with the product p', $S^{pp'} \subseteq P$

I Set of product shelf-lives (day), $I = \{1, 2, \ldots, i, \ldots, |I|\}$

Parameters

FC Fixed cost of purchasing products (currency/unit)

PC_{pt} The variable purchasing cost of product p in period t (currency/unit)

SC_{pt} Expedited service cost of product p in period t (currency/unit)

HC_{pi} Inventory holding cost of product p with age i (currency/unit)

EC_p Cost of expired/outdated product p (currency/unit)

ED_{put} Elective-demand for product p with priority u in period t (unit)

ND_{put} Non-elective demand for product p with priority u in period t (unit)

c_{pt} Maximum supplier capacity to provide product p in period t (unit)

v Total storage capacity of the medical system (unit)

m_p The storage capacity of the medical center for one unit of product p (unit)

mv_p The maximum storage capacity of the medical system for product p (unit)

η_{pu} The relative importance of the availability of product p for patients with priority u

π_{pu} The relative importance of freshness of product p for patients with priority u

$\theta_{pp'u}$ Substitution rate of product p with product p' for demand with priority u

δ_{pu} 1 if it is possible for demand with priority u to substitute product p with another product; otherwise, 0

Decision variables and outputs

Q_{pt} The order quantity for product p in period t (unit)

I_{pit} Inventory level of product p with age i in period t (unit)

A_{pit} Number of assigned/consumed inventories of product p with age i for total demands satisfaction in period t (unit)

F_{piut} Number of assigned/consumed inventories of product p with age i for satisfying demand with priority u in period t (unit)

$F'_{pip'ut}$ Amount of substitute inventories of product p with age i for satisfying demand of product p' with priority u in period t (unit)

D_{put} Total satisfied the demand for product p with priority u in period t (unit)

B_{put} Total unfulfilled demand for product p with priority u at period t, before expedited orders (unit)

X_{put} Number of expedited orders for product p with priority u in period t (unit)

Z_{put} The response rate to non-elective demands for product p with priority u in period t

E_{pt} Amount of expired product p in period t (unit)

O_t Binary variable; 1 if the system replenishes any product units in period t; Otherwise, 0

$E1$ Value of economic objective function (total system cost)

$H1$ Value of the first health objective function (shortage)

$H2$ Value of the second health objective function (substitution)

$H3$ Value of the third health objective function (non-freshness)

$H4$ Value of the fourth health objective function (non-elective demand)

4.2. The objective functions

There are five health-economic objective functions. One of them is an economic objective, and the other four are the objectives related to health equity. The

proposed model objectives are presented in the following.

4.2.1. Economic objective

The economic objective minimizes the total costs of inventory management. This function is comprised of four main parts: In the first part, the fixed and variable costs of the products as well as the purchasing costs are calculated. In the second part, the purchasing cost of products is computed using expedited service to compensate for the shortage. In the third part, the holding cost is calculated. Finally, in the fourth part, the wastage/disposal cost of the expired products is computed. Eq. (6) shows the economic objective function and its different constituents:

$$
\min E1 = \left[\sum_t FC.O_t + \sum_p \sum_t PC_{pt}.Q_{pt} \right]
$$

$$
+ \left[\sum_p \sum_t SC_{pt}.X_{pt} \right]
$$

$$
+ \left[\sum_p \sum_i \sum_t HC_{pi}.I_{pit} \right]
$$

$$
+ \left[\sum_p \sum_t EC_p.E_{pt} \right]. \tag{6}
$$

4.2.2. The first health objective

The first health objective minimizes the inventory shortage. Shortage of medical products in healthcare systems has a direct impact on the patients' health. Eq. (7) shows how the first social objective function is calculated by which the shortage is minimized:

$$
\min H1 = \sum_p \sum_u \sum_t \eta_{pu} \left(B_{put} - X_{put} \right). \tag{7}
$$

It should be noted that the value of different products for different ULs is considered to be stated in a standard manner. In addition, the lost shortage may only happen in Class 3 for the current problem.

4.2.3. The second health objective

The second health objective aims to minimize the shortage-based substitution of products in demand with the rest of available products. Eq. (8) shows the second social objective, by which the number of substitutions (specifically inappropriate substitution) is minimized.

$$
\min H2 = \sum_p \sum_i \sum_{p' S^p} \sum_u \sum_t \left(1 - \theta_{pp'u} \right) F'_{pip'ut}. \tag{8}
$$

It should be mentioned that different products can be substituted with a specific substitution rate. The sensitivity of the substitution objective function increases by decreasing the substitution rate, which leads to less substitution.

4.2.4. The third health objective

The third health objective is concerned with the freshness rate of item units assigned for demand satisfaction. This objective function is shown in Eq. (9), where the demand satisfaction with non-fresh products is minimized. The freshness of each product and each demand priority have specific values, and a product is considered non-fresh if its age is more than $\frac{|I|}{2}$. Of note, the relative importance coefficient of the freshness is multiplied by the degree of the non-freshness $\left(\frac{\left(i - \frac{|I|}{2} \right)}{|I|} \right)$ to increase the sensitivity to the non-fresh units.

$$
\min H3 = \left(\sum_p \sum_{i > \frac{|I|}{2}} \sum_u \sum_t \frac{\pi_{pu} \left(i - \frac{|I|}{2} \right)}{|I|} F_{piut} \right.
$$

$$
\left. + \sum_p \sum_i \sum_{p' S^p} \sum_u \sum_t \frac{\pi_{pu} \left(i - \frac{|I|}{2} \right)}{|I|} F'_{pip'ut} \right). \tag{9}
$$

4.2.5. The fourth health objective

The fourth health objective is stated in Eq. (10) according to which the level of non-response to non-elective demands is minimized. Note that π_{pu} indicates the importance of each product for patients at each UL. This coefficient increases the response to emergency patients with high priority.

$$
\min H4 = \sum_p \sum_u \sum_t \eta_{pu} \left(1 - Z_{put} \right).ND_{put}. \tag{10}
$$

Five health-economic objectives are employed to model the current problem, including one economic and four health objectives concerned with healthcare equity. Classic approaches mostly consider shortage as cost in their economic objective. However, given the importance of shortage in this research, this objective is considered independently.

4.3. Model constraints

Relations (11)–(34) address the constraints of the proposed model. In the following, each constraint will be described in detail.

4.3.1. Order quantity

Constraint (11) shows the limited supply capacity, remarking that the order quantity can be equal to or less than the supply capacity. Moreover, Constraint (11) ensures that O_t equals 1 even if a single product unit is ordered from the blood center on day t; otherwise, it equals 0. Constraint (12) ensures that the replenishment only occurs during the allowed review periods. Note that if $R = T$, Constraint (12) is not necessary.

Constraint (13) expresses that the total order quantity of the fresh units in period $t-1$ equals the assigned units for demand satisfaction plus stock-on-hand in the end period t. Note that the received products by the blood bank at the beginning of the day t are assumed to be fresh, and they are in the first period of their shelf-life. Moreover, the lead time during which the order quantity is received from the supplier is considered one day.

$$Q_{pt} \leq c_{pt}.O_t; \quad \forall p \in P, t \in T, \tag{11}$$

$$O_t = 0; \quad \forall t \notin R, \tag{12}$$

$$Q_{pt-1} = Y_{p1t} + I_{p1t}; \quad \forall p \in P, t \in T. \tag{13}$$

4.3.2. Inventory updates
Constraint (14) shows that the stock-on-hand of a given item with the remaining shelf-life of $i-1$ days at the end of the period $t-1$ equals the summation of the assigned units for demand satisfaction and stock-on-hand with shelf-life of i days at the end of the period t of the planning horizon.

$$I_{p(i-1)t-1} = A_{pit} + I_{pit};$$
$$\forall p \in P, i \in I - \{1\}, t \in T. \tag{14}$$

4.3.3. Assigned/consumed inventory
Constraint (15) indicates the allocation and substitution of product p units with shelf-life of i days to meet the demands of class u on day i of their shelf-lives during the period t of the planning horizon.

$$A_{pit} = \sum_u F_{piut} + \sum_{p' S^p} \sum_u F'_{pip'ut};$$
$$\forall p \in P, i \in I, t \in T. \tag{15}$$

4.3.4. Demand constraints
Constraint (16) calculates the total satisfied demand of product p in class u and the period t of the planning horizon. Of note, the unfulfilled demand at class u is considered as shortage, i.e., B_{put}, in period t and it might be compensated by shortage-based substitution, expedited-order, or remain as lost depending on the demand class, which is predetermined and modeled by the following constraints.

Constraint (17) shows how to satisfy the demand at class u for product p on day t of the planning horizon. In other words, Constraint (17) indicates how the demands for product p are met by the same requested product and with other substitutable products if allowed.

$$D_{put} = ED_{put} + Z_{put}.ND_{put} - B_{put};$$
$$\forall p \in P, u \in U, t \in T, \tag{16}$$

$$\sum_i F_{piut} + \sum_{p' S^p} \sum_i F'_{p'iput} = D_{put};$$
$$\forall p \in P, u \in U, t \in T. \tag{17}$$

4.3.5. Shortage-based expedited order policy
Constraint (18) expresses that when demand at classes $u = 1, 2$ encounters shortage for the product p, it must be satisfied through an expedited order policy. In this case, an extra order must be taken through expedited service. However, according to Constraint (19), it is unnecessary to compensate for the unfulfilled demand at class $u = 3$. Note that the first health objective function (shortage) tends to compensate unfulfilled demand at class $u = 3$ by ordering through expedited service.

$$X_{put} = B_{put}; \quad \forall p \in P, u \in U - \{3\}, t \in T, \tag{18}$$

$$X_{p3t} \leq B_{p3t}; \quad \forall p \in P, t \in T. \tag{19}$$

4.3.6. Expired/outdated items
Constraint (20) calculates the number of expired units in the period t of the planning horizon. Accordingly, the inventory of units at the end of the period $t-1$, which is in the last period of its shelf-life, is considered as the expired unit in the period t of the planning horizon.

$$E_{pt} = I_{p|I|t-1}; \quad \forall p \in Pt \in T. \tag{20}$$

4.3.7. Capacity constraints
Constraints (21) and (22) address the total storage capacity of the system and storage capacity limitation of each product, respectively, in the period t of the planning horizon. Note that the storage capacity of blood banks is limited because blood products need outstanding storage facilities.

$$\sum_p \sum_i m_p.I_{pit} \leq v; \quad \forall t \in T, \tag{21}$$

$$\sum_i m_p.I_{pit} \leq mv_p; \quad \forall p \in P, t \in T. \tag{22}$$

4.3.8. Substitution policy
Constraint (23) guarantees that the demand at $u = 1$ will be satisfied. As long as there is a shortage of product p for demand at class $u = 1$, it is not possible to meet the demand of other classes. Similarly, Constraint (24) guarantees the priority of class $u = 2$ over $u = 3$. Note that if $\eta_{p1} > \eta_{p2} > \eta_{p3}$, the second objective function satisfies Constraints (23) and (24) in optimality.

Constraint (25) shows how product substitution based on the medical priorities can be performed at any ULs. For instance, in case it is not possible to substitute any product at $u = 1$, we have $\sum_i F'_{pip'ut} = 0$. Note that M is a very big number.

$$B_{p1t} > 0 \Rightarrow \sum_{u>1} F_{piut} + \sum_{p' \epsilon S^p} \sum_{u>1} F'_{pip'ut} = 0;$$

$$\forall p \in P, i \in I, t \in T, \qquad (23)$$

$$B_{p2t} > 0 \Rightarrow \sum_{u>2} F_{piut} + \sum_{p' \epsilon S^p} \sum_{u>2} F'_{pip'ut} = 0;$$

$$\forall p \in P, i \in I, t \in T, \qquad (24)$$

$$\sum_i F'_{pip'ut} \leq \delta_{pu} M;$$

$$\forall p \in P, p' \epsilon S^{pp'}, u \in U, t \in T. \qquad (25)$$

4.3.9. Issuance and allocation policy
Constraint (26) addresses the LEFO issuance policy for demand satisfaction at class $u = 1$. In this regard, the items of product p with a shelf-life of $j > i$ days should not be used to satisfy the demand until the quantity of the product p inventory with a shelf-life of i days is exhausted. Note that the demands in Class 1 must be satisfied with the freshest items.

$$I_{pit} > 0 \Rightarrow \sum_{j>i} F_{pjut} = 0;$$

$$\forall p \in P, i \in I, t \in T, [u = 1]. \qquad (26)$$

Constraint (27) shows that Constraint (26) is linear in form. Note that in Constraint (27), ℓ_{pit} is a binary variable, which equals 1 if $I_{pit} > 0$. In Constraint (27), M and eps are a positive big enough number and a very small number, respectively.

$$\begin{cases} \ell_{pit} \geq \frac{I_{pit}}{M}; & \forall p \in P, i \in I, t \in T \\ \ell_{pit} \leq 1 + \frac{I_{pit}-eps}{M}; & \forall p \in P, i \in I, t \in T \\ \sum_{j>i} F_{pjut} \leq (1 - \ell_{pit}) M; & \forall p \in P, i \in I, t \in T, \\ & [u = 1] \\ \ell_{pit} \in \{0, 1\} & \end{cases} \qquad (27)$$

Constraints (28) and (29) address how both FEFO and LEFO issuance policies are applied to satisfy the demand at $u = 2$. Constraint (28) indicates that the fresh product units (with a shelf-life of fewer than $I/2$ days) must be issued based on the FEFO policy. In this way, the product units with a shelf-life of $j < i$ days should not be used for demand satisfaction until the inventory with a shelf-life of i days is exhausted. Constraint (29) indicates that the fresh product units (with a shelf-life of more than $I/2$ days) must be issued based on the LEFO policy. In this way, the product units with a shelf-life of $j > i$ days should not be used for demand satisfaction until the inventory with a shelf-life of i days is exhausted. Note that in order to reduce the risk of lives, it is suggested to use the fresh items

with LEFO policy and ordinary product with FEFO policy for Class 2.

$$I_{pit} > 0 \Rightarrow \sum_{j<i} F_{pjut} = 0;$$

$$\forall p \in P, i \leq \frac{|I|}{2}, t \in T, [u = 2], \qquad (28)$$

$$I_{pit} > 0 \Rightarrow \sum_{j>i} F_{pjut} = 0;$$

$$\forall p \in P, i > \frac{|I|}{2}, t \in T, [u = 2]. \qquad (29)$$

Constraints (30) and (31) convert Constraints (28) and (29) to linear form. Similarly, in Constraints (30) and (31), ℓ_{pit} is a binary variable, which equals 1 if $I_{pit} > 0$. In these constraints, M and are eps are the positive big enough and very small numbers, respectively.

$$\begin{cases} \ell_{pit} \geq \frac{I_{pit}}{M}; & \forall p \in P, i \in I, t \in T \\ \ell_{pit} \leq 1 + \frac{I_{pit}-eps}{M}; & \forall p \in P, i \in I, t \in T \\ \sum_{j<i} F_{pjut} \leq (1 - \ell_{pit}) M; & \forall p \in P, i \leq \frac{|I|}{2}, t \in T, \\ \ell_{pit} \in \{0, 1\} & [u = 2] \end{cases} \qquad (30)$$

$$\begin{cases} \ell_{pit} \geq \frac{I_{pit}}{M}; & \forall p \in P, i \in I, t \in T \\ \ell_{pit} \leq 1 + \frac{I_{pit}-eps}{M}; & \forall p \in P, i \in I, t \in T \\ \sum_{j>i} F_{pjut} \leq (1 - \ell_{pit}) M; & \forall p \in P, i > \frac{|I|}{2}, t \in T, \\ & [u = 2] \\ \ell_{pit} \in \{0, 1\} & \end{cases} \qquad (31)$$

As already mentioned, to meet the patients' demand for products at Class $u = 3$ based on the OP, the model itself decides which part of the inventory at the storage should be issued. Note that there is no difference between the demands in Class 3 in terms of freshness. Nevertheless, if the FEFO issuance policy is considered for demand assignment in Class $u = 3$, Constraint (32) should be taken into account. In this case, the production unit with a shelf-life of $j < i$ days should not be used for demand satisfaction until the product inventory with a shelf-life of i days is exhausted.

$$I_{pit} > 0 \Rightarrow \sum_{j<i} F_{pjut} = 0;$$

$$\forall p \in P, i \in I, t \in T, [u = 3]. \qquad (32)$$

Constraint (33) converts Constraint (32) in linear form.

$$\begin{cases} \ell_{pit} \geq \frac{I_{pit}}{M}; & \forall p \in P, i \in I, t \in T \\ \ell_{pit} \leq 1 + \frac{I_{pit}-eps}{M}; & \forall p \in P, i \in I, t \in T \\ \sum_{j<i} F_{pjut} \leq (1 - \ell_{pit}) M; & \forall p \in P, i \in I, t \in T, \\ & [u = 3] \\ \ell_{pit} \in \{0, 1\} & \end{cases} \qquad (33)$$

4.3.10. Non-negativity

Constraint (34) represents the non-negativity and binary restrictions in the model.

$$
\begin{cases}
O_t, \ell_{pit} \in \{0, 1\} \\
Q_{pt}, I_{pit}, A_{pit}, F_{piut}, F'_{pip'ut}, G_{put}, \\
\quad D_{put}, B_{put}, W_{put}, E_{pt} \geq 0, \ G_{put} \leq 1
\end{cases}
\tag{34}
$$

4.4. Solution approach

An extended GP approach is employed to make a trade-off between the objective functions of the proposed model. In this regard, the previously defined payoff matrix between the health-economic objectives should be obtained in the beginning. The proposed model is first solved four times, each of which comprises only one of the considered objectives in terms of a single-objective problem. To find the appropriate interval corresponding to the ith objective ($i = 2, \ldots, n$), the following optimization problem should be solved for each objective, $j = 1, 2, \ldots, n$:

$$
\begin{aligned}
PayOff_{jj} &= \min f_j(x) \\
x &\in X
\end{aligned}
\tag{35}
$$

where $x^{j,*}$ stands for the optimal solution, and $PayOff_{jj} = f_j(x^{j,*})$ the optimal value of the jth objective. Then, the optimal value of the ith objective can be obtained by finding the optimal value of each objective ($j = 1, 2, \ldots, n \ \ ; j \neq i$) as follows:

$$
\begin{aligned}
PayOff_{ij} &= \min f_i(x) \\
f_j(x) &= PayOff_{jj} \\
x &\in X \\
j &\neq i,
\end{aligned}
\tag{36}
$$

where $x^{i,j,*}$ and $PayOff_{jj} = f_i(x^{i,j,*})$ are the optimal solution and optimal value, respectively, belonging to the ith objective. Accordingly, the payoff matrix is obtained as follows:

$$
PayOff = [PayOff_{ij}].
\tag{37}
$$

Followed by determining the payoff matrix for each objective ($i = 1, 2, \ldots, n$), the following items are defined as:

- $\mathrm{Min}(f_i) = \min_j \{PayOff_{ij}\} = PayOff_{ii}$;
- $\mathrm{Max}(f_i) = \max_j \{PayOff_{ij}\}$;
- $R(f_i) = \max(f_i) - \min(f_i)$.

The value of $R(f_i)$ is used to normalize the objectives in MODM objective function. Assume that the following values are obtained using the objectives payoff matrices:

$\underline{F_1}$ The minimum value of the first objective (optimal)

$\overline{F_1}$ The maximum value of the first objective

$\underline{F_2}$ The minimum value of the second objective (optimal)

$\overline{F_2}$ The maximum value of the second objective

$\underline{F_3}$ The minimum value of the third objective (optimal)

$\overline{F_3}$ The maximum value of the third objective

$\underline{F_4}$ The minimum value of the fourth objective (optimal)

$\overline{F_4}$ The maximum value of the fourth objective

Next, through the GP approach, the MODM model can be stated in terms of a single-objective one, as shown in Relation (38):

$$
\begin{cases}
GP \text{ for } MOMILP \\
\min Z \\
Z \geq \dfrac{Z^{E1} - \underline{F_1}}{\overline{F_1} - \underline{F_1}} \\
Z \geq \dfrac{Z^{H1} - \underline{F_2}}{\overline{F_2} - \underline{F_2}} \\
Z \geq \dfrac{Z^{H2} - \underline{F_3}}{\overline{F_3} - \underline{F_3}} \\
Z \geq \dfrac{Z^{H3} - \underline{F_4}}{\overline{F_4} - \underline{F_4}} \\
Z \geq \dfrac{Z^{H4} - \underline{F_5}}{\overline{F_5} - \underline{F_5}} \\
x \in X \\
MOMILP \text{ Constraints } (11) - (34)
\end{cases}
\tag{38}
$$

Note that the final multi-objective model is an MILP model based on the GP approach. It can be solved using CPLEX solver in General Algebraic Modelling System (GAMS).

5. Case study

This section presents a real case from Iran to validate the proposed mathematical model and evaluate its possible practicality. Iran is among the countries where blood donation is volunteer-based; hence, the amount of donated blood is strongly reliant on blood donors [32]. In this respect, donors' low participation is always exposing the country's BSC to the risk of blood shortage. Previous studies on Iran's BSC and its challenges highlight the need for improving knowledge and activities related to blood management and its possible alternatives [15,18].

Iranian Blood Transfusion Organization (IBTO) is the only blood processor and supplier in Iran, called the blood center. IBTO is located in Tehran, the capital of Iran, and serves in-home hospitals directly. As the case study, a leading Cardiovascular
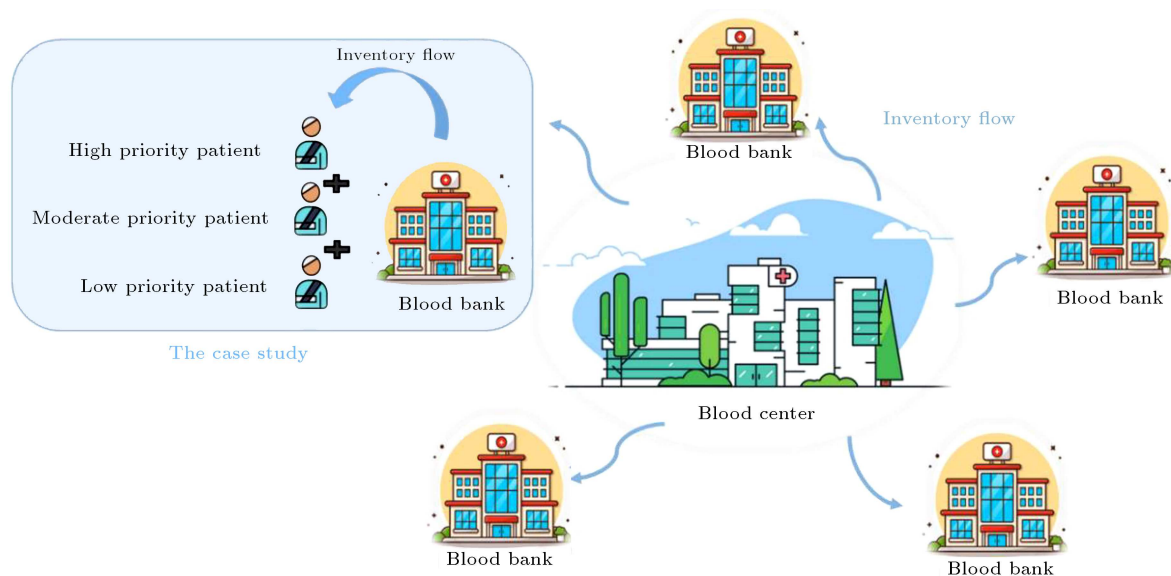
Figure 3. The case study scope.

hospital in Tehran is considered. The hospital is one of the biggest cardiovascular, medical, and research centers in west Asia with a 24-hour emergency center. Therefore, the hospital encounters both elective and non-elective demands.

The mentioned hospital offers preventive, diagnostic, and therapeutic services. In this direction, it deals with patients at different levels of medical urgency. In addition, heart transplants surgeries are performed at the cardiovascular center of this hospital. Most heart disease patients refer to this hospital since they offer a wide diversity and healthcare scope for patients. There are about 600 active beds in here. The management team of its blood bank is responsible for controlling, policy-making, planning, and ordering the inventory of blood-base products required by various departments to IBTO [35]. Moreover, the storage capacity of the blood bank and supply capacity of the IBTO are limited. Figure 3 illustrates the relation between the IBTO and proposed blood bank.

The products under study are platelet-derived products with a shelf-life of five days and ABO/Rh blood group types. The researchers collected the required data through a previous study on the process model of the hospital blood bank. In this regard, the historical data of the blood bank, IBTO statistical reports, and experts' opinions were taken into consideration [35]. The data used in this study were collected at the time of the outbreak of Coronavirus disease (Covid-19 pandemic). Tables A.1–A.4 present the parameter values for the system under study in the proposed model.

6. Computational results and evaluation

In this section, the inspired data from the predefined case study is applied to the problem. Then, the validity of the model implementation is assessed, and the results are presented. In this research, an MOMILP model is proposed to handle the problem and then, it is solved using a GP approach. The model is coded in GAMS and solved by CPLEX solver on a personal computer with Intel Core i5 8400 processor, 8 GB RAM, and SSD 120 GB.

6.1. Implementation and discussion

In this part, the investigated problem is solved based on the approach described in Subsection 4.4. Validation of the proposed model is done in a real case study. The performance of the presented model is then compared with the single-objective models of each objective. In this regard, the proposed model is first solved five times, each of which comprises only one of the considered objectives in terms of a single-objective problem. Then, the multi-objective model is solved using a GP approach. Finally, the obtained results are discussed. A summary of the obtained results is given in Table 2 and graphically compared in Figure 4.

Further, some sensitivity analyses are conducted on some of the main parameters of the problem to assess the performance of the proposed model. The obtained results help DMs find proper solutions for the problem.

In order to solve the problem using the GP approach, the payoff matrix should be first obtained. Next, as already explained in Section 4.4, the objective function value is attained for the multi-objective model using the payoff matrix. Table 2 addresses the obtained values. The SO and MO notations in the following tables and figures refer to the single- and multi-objective models, respectively.

Figure 4 compares the results obtained from

Table 2. Result summary of the single- and multi-objective models.

Objective	SO-E1	SO-H1	SO-H2	SO-H3	SO-H4	MO
E1	4325124	3933183	3766040	7877281	3044508	4413957
H1	27966	27377	30123	0	30810	8730
H2	281	209	0	480	120	114
H3	342	0	20	256	0	22
H4	0	12878	12941	18367	22306	6321
MO	–	–	–	–	–	0.283
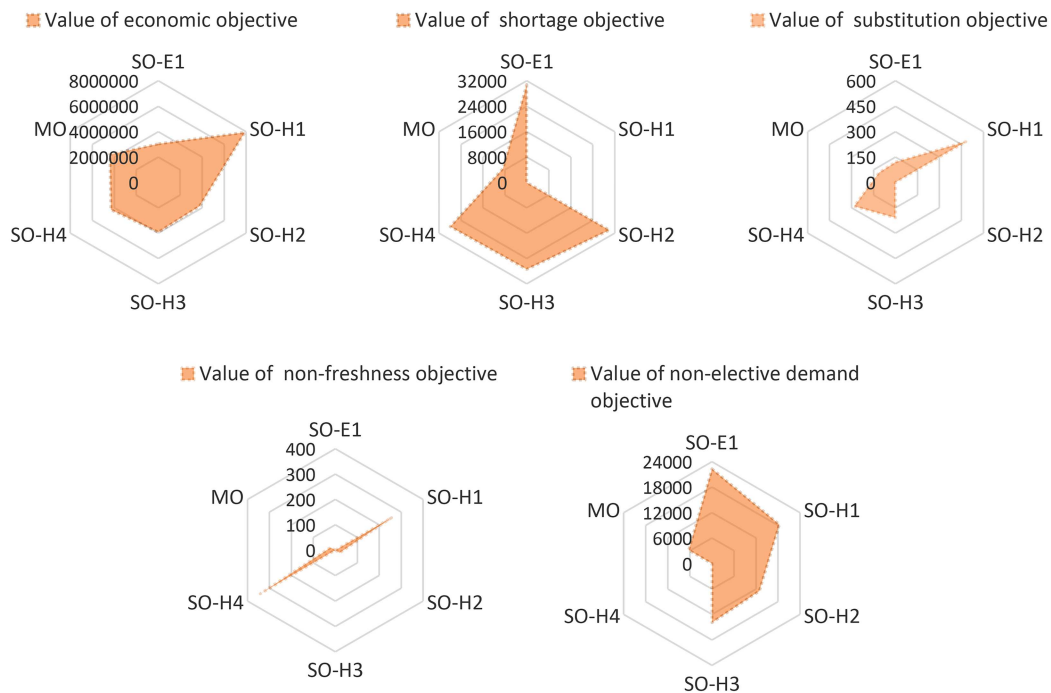
Figure 4. Comparison of obtained values for five health-economic objectives by solving single-objective models.

solving single- and multi-objective models. In case only one objective is considered, the model obtains the best possible solution to that objective. In this case, according to the results demonstrated in Table 2 and the plots in Figure 4, a proper solution is often not obtained for other objectives. The main challenge here is to make a trade-off among all objectives to get the best possible solution when several objectives are simultaneously considered. According to Figure 4, compared to other single-objective models, the multi-objective model performs well in this regard.

Figure 5 presents the solutions to the order quantity and shortage obtained from single- and multi-objective models in a 30-day planning period. According to the results, larger order quantities are generally required to achieve less shortage. All unsatisfied demands in the single-objective model of shortage are compensated by imposing expedited-service costs through expedited order to the IBTO. However, no expedited order occurs for other single-objective models. In these cases, all shortage amounts are lost. The
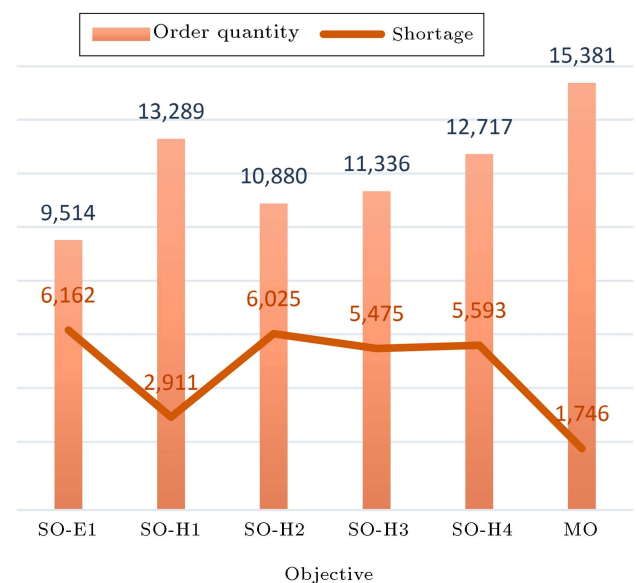
Figure 5. Obtained solutions for order quantity and shortage by solving single- and multi-objective models.
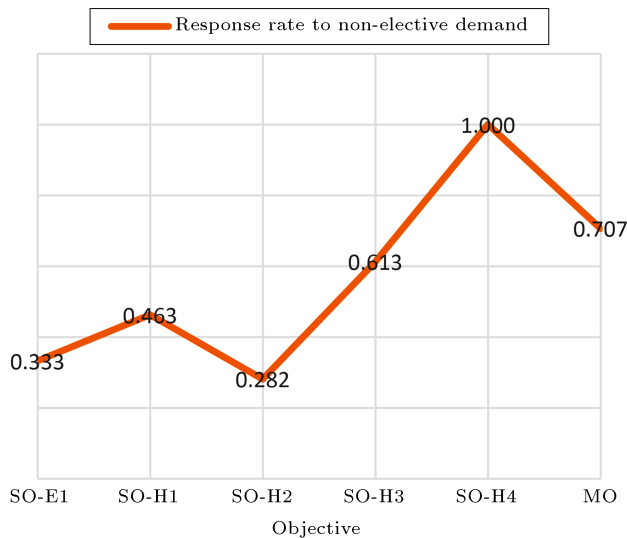
Figure 6. The response rate to non-elective demand for single- and multi-objective models.

results show that the shortage amount in the proposed multi-objective model is significantly less than in other single-objective models.

The single-objective model aiming to minimize total system costs is an extended Economic Order Quantity (EOQ) model. The EOQ model shortens the replenishment periods to decrease the total fixed-order cost in the system. In this regard, solving the single-objective economic model indicates that the number of replenishment periods over the planning horizon is equal to 17. For other single-objective models related to health equity, it is equivalent to all allowed periods. However, for the proposed multi-objective model, replenishment is done in 18 periods to reduce the ordering fixed-cost. As the number of ordering periods decreases, the ordering quantities will relatively increase.

Figure 6 compares the rate of responding to non-elective demands for health-economic single- and multi-objective models. According to the observations, the mentioned rate for the single-objective model related to non-elective demands is equal to 100%. Therefore, it can be concluded that all non-elective demands are satisfied by this objective, hence an optimum solution. Next, the proposed multi-objective model reaches the best solution for this health objective by meeting more than 70% of non-elective demands.

Moreover, for the first health-objective function, the response rate to non-elective demand is 46%, which is higher than the rest of the single-objective models. This objective function is related to shortage minimization. Note that the shortage may occur for both elective and non-elective demands. In this case, the shortage objective function aims to respond to non-elective demand as much as possible.

Figure 7 indicates how the demands at different

classes are fulfilled by the single- and multi-objective models. According to the assumptions in the problem under study, substitution is not allowed for the demands of the first class. However, for the other two classes, substitution depends on the medical preferences. In this case, the substitution single-objective model gets the optimum solution. The results confirm that the proposed multi-objective model obtains the least substitution value among the other single-objective models. The worst-case scenario belongs to the shortage objective. Note that the substitution rate increases to reduce the lost demands in case of shortage.

As demonstrated in Figure 8, most of the items assigned to satisfy the demands are nearly fresh for all health-economic single- and multi-objective models. The objectives related to the shortage and non-elective demands in the single-objective form satisfy a small part of demands with non-fresh items. The proposed model is designed to consume the inventory before its expedition, if possible. Solving the proposed model verifies that the inventory is planned to ensure that the wastage amount is optimal and equal to zero.

However, solving the economic single-objective model indicates that the freshness of items is less than the other models, but still considered fresh. It is due to the nature of EOQ models. Note that in this case, the model reduces the number of replenishment periods to decrease the ordering fixed cost.

In this paper, the proposed multi-objective model is first solved using a GP approach with the same importance for all objectives. Next, the effect of the weight of the objectives on the results is investigated to provide a comprehensive insight for decision-makers. Table 3 presents the effect of the weight of the health-economic objectives on the obtained results.

Assume that there is no fiscal constraint for the system, and only the non-economic objectives are necessary for the system. In this case, Table 3 demonstrates that all the objectives related to health equity get near-optimal solutions. Nevertheless, the total system costs significantly increase. In this respect, the non-freshness objective has multi-optimal solutions.

According to Table 3, once the economic objective is optimized, the freshness objective obtains an optimal solution. Note that the weight of the economic objective function decreases; in this case, as the total system costs increase, the shortage will decrease, and the substitution rate will increase. The weight reduction in the shortage objective function leads to a significant decrease in the total system costs. Upon decreasing the weight of the substitution objective, the total system costs and shortage amounts will significantly decrease. Assigning greater importance to the non-freshness objective does not have a positive impact on the other health objective functions.

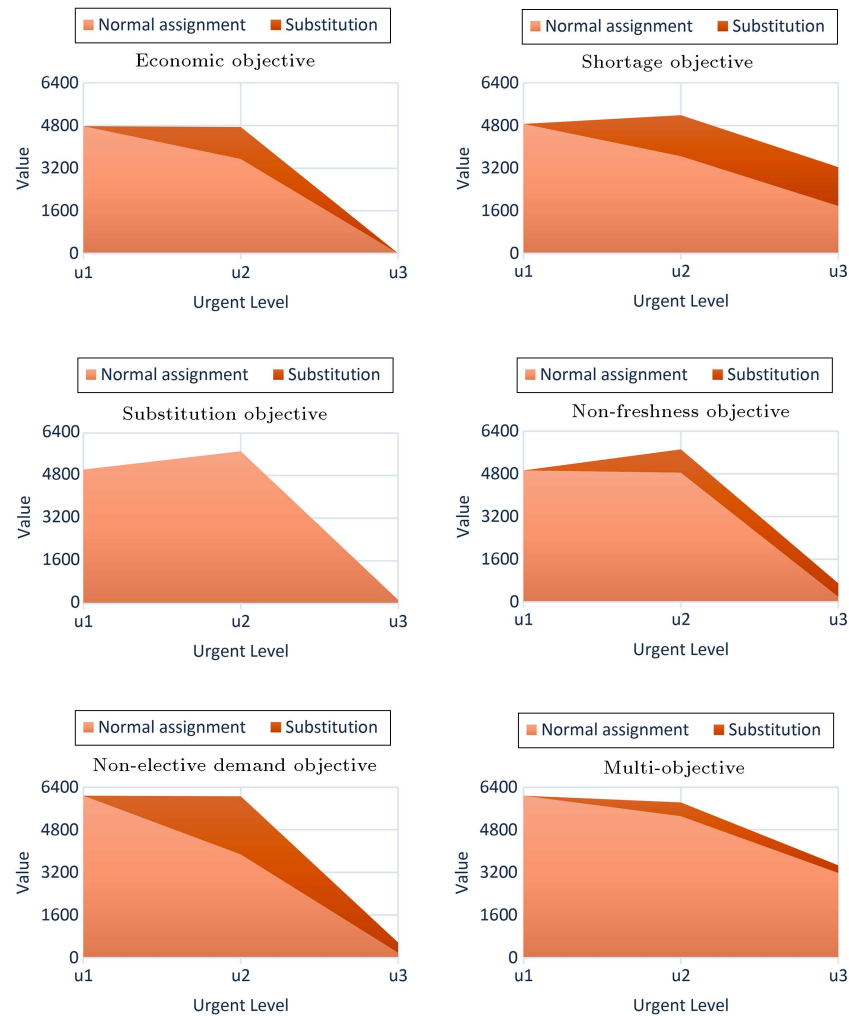Most of the classic models focus only on cost

Figure 7. How to assign inventory to different levels of demand urgency for single- and multi-objective models.
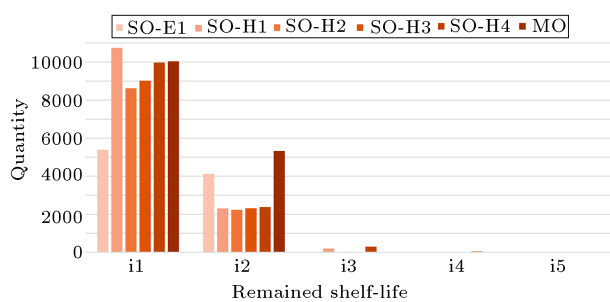

Figure 8. The freshness of the assigned products for single- and multi-objective models.

Figure 9. Results of changing expedited-order cost (which is considered as a proportion of variable purchasing cost) on normal/expedited order quantity, shortage, and lost demand.

and shortage minimization. In this case, most non-elective demands remain unsatisfied. In addition, the substitution rate gets very high. Followed by reducing the weight of the economic objective, better solutions are obtained for the health equity objectives.

Figure 9 illustrates the effect of the expedited service cost (to compensate for the shortage) on the solution of normal order quantities, expedited order quantities, shortage amounts, and lost demands. In-
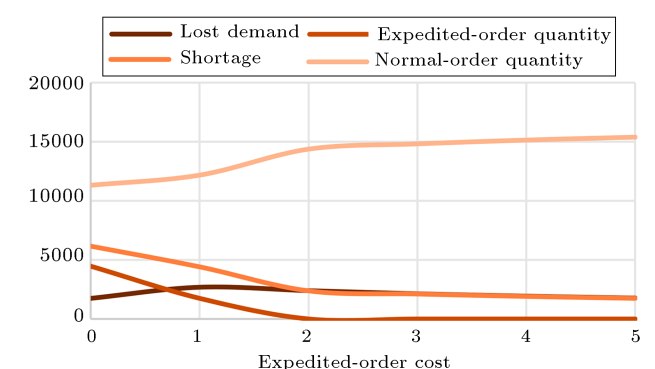
creasing the expedited service cost affects the system's total costs related to inventory management and lost demands.

As discussed in the literature, the expedited service cost is usually high. As long as the expedited

Table 3. Results of changing the health-economic objectives' weights on the optimal solution of the multi-objective model.

$(w1, w2, w3, w4, w5)$	$E1$	$H1$	$H2$	$H3$	$H4$	Q_{pt}	B_{put}	X_{put}	E_{put}
(1,0,0,0,0)	3044508	30810	120	0	22306	9514	6162	0	0
(0.5,0.5,0,0,0)	3882147	5340	215	3.69	28852	13301	1064	0	0
(0.4,0.3,0.1, 0.1,0.1)	4000081	8123	147	0	17642	13954	1625	0	0
(0.3,0.4,0.1, 0.1,0.1	4210884	5577	166	20	16151	1641	1116	0	0
(0.2,0.2,0.1,0.1,0.3)	4633198	6752	198	3.16	4889	16031	1348	0	0
(0.2,0.2,0.2,0.2,0.2)	4413957	8730	114	22	6321	15381	1746	0	0
(0.1,0.4,0.1,0.1,0.3)	5022620	3153	196	0	3043	17154	631	0	0
(0,1,0,0,0)	7877281	0	480	256	18367	13289	2911	2911	0
(0,0.5,0,0,0.5)	8368413	0	579	178	0	15338	2978	2978	3
(0,0.4,0.1,0.1,0.4)	8536463	38	2.37	1.69	28	14681	3617	3609	0
(0,0.3,0.3,0.1,0.3)	7820352	107	1.66	2.59	77	15683	2615	2593	4
(0,0.25,0.25,0.25,0.25)	8617606	107	1.66	1.19	77	13251	3760	3738	5
(0,0,1,0,0)	3766040	30123	0	20	12941	10880	6025	0	0
(0,0,0,1,0)	3933183	27377	209	0	13878	11336	5475	0	0
(0,0,0,0,1)	3425124	27966	281	342.2	0	12717	5593	0	0

Table 4. Results of changing the product availability importance (η_{pu}) on the solution of the multi-objective model during the planning horizon.

$(u1, u2, u3)$	$E1$	$H1$	$H2$	$H3$	$H4$	Q_{pt}	B_{put}	Z_{put}
(10,10,10)	4491788	18453	143	0	7859	15671	1848	0.82
(10,10,5)	4398666	8633	134	5.735	7354	15189	1732	0.975
(10,7,7)	4436957	12964	151	0	6704	15490	1856	0.777
(10,7,5)	4413957	8730	114	22	6321	15381	1746	0.707
(10,5,5)	4417825	8755	119	0.29	5593	15431	1754	0.713

service cost is less than two times the variable purchasing cost, the model tends to meet the shortage of product units by receiving the expedited services. Accordingly, as the expedited service cost increases, the model prefers to order more quantities to face fewer shortage amounts and avoid using the expedited services as much as possible. It should be noted that the expedited service cost gets more than two times the variable purchasing cost and in this case, more quantities are ordered, and the amounts of lost demand and shortage will overlap.

The proposed model is designed to highlight the importance of the product availability for Class 1 and Class 2. If the inventory system at these two levels faces a shortage in demand satisfaction, the required item units will be immediately supplied by imposing the cost of the expedited services. In this case, Constraints (23) and (24) are relaxed; only the value of η_{pu} affects the importance of product availability and shortage of the two first levels of medical urgency. Moreover, the obtained solution does not necessarily lead to

the unfulfilled demand satisfaction through expedited services when the system faces a shortage.

The effect of the value of parameter η_{p3} on the solution of the proposed multi-objective model is investigated, and the obtained results are reported in Table 4. The results show that the values of wastage and expedited order are zero in all cases.

Figure 10 demonstrates the effect of fixed purchasing cost on the order quantity and shortage by solving the proposed multi-objective model. It also indicates the relation between the replenishment periods and order quantity by increasing the fixed purchasing cost. The higher the mentioned cost, the smaller the number of ordering periods and the higher the order quantity in each period. The larger amount of order quantities straightly impacts the shortage. In other words, the higher the order quantity, the lower the shortage. Up to $FC = 50000$, the number of replenishment periods gradually decreases. Similarly, the order quantity gradually increases, while the amount of shortage decreases. At higher values of $FC = 50000$, the replenishment
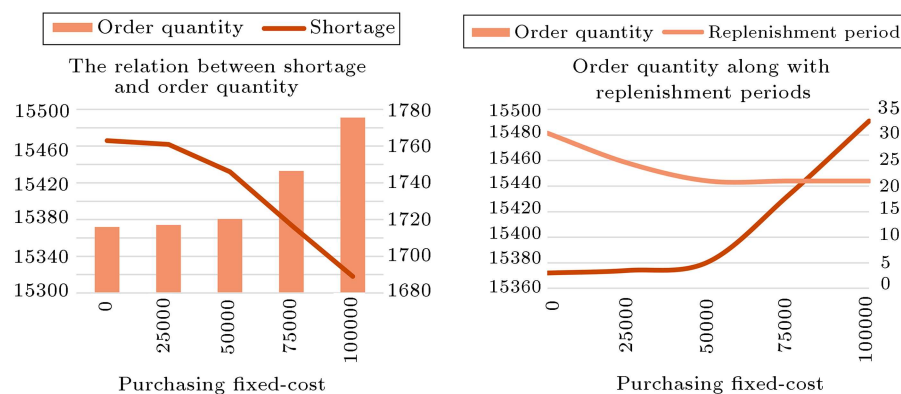
Figure 10. Results of changing purchasing fixed-cost on order quantity, shortage, and replenishment periods.

periods will remain steady. Nevertheless, after this point, the order quantities instantly increase with a steep slope. The amount of shortage exhibits opposite behavior to that of the order quantity.

6.2. Managerial insights

This paper proposed a comprehensive inventory management model for hospital blood banks to select logistical tactics, inventory levels, and supply chain designs. The model was examined in a real case study to evaluate its validity. In addition, some sensitivity analyses were conducted to evaluate the performance of the model to provide decision-makers with a brighter insight. Several statements are given below to help managers better understand the benefits of the proposed model and its obtained solution and make appropriate decisions. The most important insights of this paper are summarized below:

- Making appropriate inventory management decisions when the healthcare system pursues multiple and contradictory health-economic objectives related to financial resources and health equity;

- Applying the concepts of health equity to blood inventory management pragmatically;

- Considering the medical priorities of patients in meeting the blood demands and adopting appropriate issuance and allocation policies in this regard;

- Making a trade-off between the total costs of the system and equity in health by eliminating unnecessary operational costs without weakening the level of service delivery in the system where all health and economic objectives are influential;

- Establishing an efficient blood inventory management model to improve the medical services, expedite treatments, and avoid the risk of lives.

- Making optimal decisions about the order quantities and replenishment periods for a real healthcare system to guarantee the least wastage and shortage in the system;

- Adopting an appropriate heuristic policy to deal with non-elective and emergency demands;

- Preparing the data needed for logistic plans and operational infrastructure for adopting an effective logistical strategy for blood products.

7. Conclusions and future studies

The ultimate purpose of the blood banks was to provide blood products in the required quantity and right time to guarantee the minimum shortage and wastage. Making a trade-off between the system costs and equity objectives without weakening the service quality is one of the most challenging healthcare issues. In this regard, this investigation presented a practical demand-oriented health-economic Multi-Objective Mixed-Integer Linear Programming (MOMILP) model for blood inventory management of a healthcare system. In addition, an effective hybrid heuristic was extended to issue and allocate the blood for demands at different urgent classes optimally and to minimize product substitution, shortage, and wastage. Moreover, fresher inventory items were used for patient treatment. This paper is the first operational research study investigating issues related to health equity in order to provide a desirable level of accessibility of medical services in terms of inventory management. In this regard, some practical strategies and policies were proposed that proved to be beneficial for handling the shortage of substances of human origin and critical medicines during the Covid-19 pandemic.

In this research, an extended Goal Programming (GP) technique was employed to obtain the optimal solution. Three demand classes were considered based on the medical priorities to implicate equity in health pragmatically. In addition, the proposed model took into account the non-elective demands and offered a solution to deal with emergency conditions. The presented model was implemented on a real case study in Iran. Some sensitivity analyses were then

conducted on the main parameters to evaluate the model performance and provide practical insight for decision-makers.

The results revealed the satisfactory performance of the proposed health-economic trade-off. They also showed that in the case of considering each objective independently in a single-objective format, the optimal solution would be obtained. Nevertheless, for other objectives, the fitness of the solution was mostly not appropriate. According to findings, the proposed multi-objective model obtained the best solution when all objectives were considered together. Hence, the proposed model provided a proper solution to meet demands with different priorities.

This investigation helps the managers efficiently consider health equity along with economic objectives. The model contributes to achieving inventory management strategies that are beneficial to meet the system demands more desirably and prevent blood loss as much as possible. Our proposed policy seeks to satisfy the patient's demands with minimum mismatches and treatment risks. The presented model also helps the managers to act decisively for blood inventories and increase the medical service level to the desired level. The findings can assist in selecting the logistical tactics, inventory policies, and supply chain designs. The presented model can also be employed to design and improve blood decision support systems.

In recent years, Blood Supply Chain (BSC) has been exposed to a decline in the number of blood donors due to the COVID-19 pandemic, resulting in a more significant shortage of blood resources. This issue adds to the importance of applying equitable policies in blood allocation. Future research studies should focus on the blood inventory management strategies and practical implementation of health equity during the pandemics. To do so, one can consider the whole BSC network or different hierarchical levels and use different modeling approaches and solution techniques. Integrating the concept of resilience into the solution methodology design by testing the proposed model behavior on unexpected disruptions in blood banks could be a future stream. In this regard, developing the proposed model for handling real-world uncertainties could be interesting for future research. Designing and optimizing a sustainable integrated BSC network considering health equity is another research topic. Moreover, human origin substances other than the blood are susceptible due to supply constraints and high demand levels. Extending and evaluating the proposed model for such products is highly encouraged.

The take-home message is to classify the demand priorities for the limited blood resources to minimize the risk of life and promote health services. Those who are responsible for the logistics and inventory of a blood bank are expected to ensure the correct replenishment of the blood products, when needed, with the quality and quantity intended to provide healthcare service. Hence, they are looking for practical strategies to avoid the risk of lives and ensuring that the whole process is carried out in the most effective and efficient way. They also need to look for opportunities to improve inventory management processes to reduce costs and improve medical service continually. In this regard, managing inventory is imperative to identify and correct the logistic deficiencies.

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Appendix A

In this section, the values of the parameters for the proposed model have been addressed, considering the system under study specifications. Table A.1 represents the substitution rate of different products to satisfy demand in class 3. Table A.2 shows the variable purchasing cost of product p, which remains the same for each period t. Table A.3 specifies the values of the remaining parameters, while Table A.4 outlines the product substitution allowances based on medical priorities.

Table A.1. Substitution rate of product p with product p' for demand at class 3.

$\theta_{pp'3}$	$p' = 1$	$p' = 2$	$p' = 3$	$p' = 4$	$p' = 5$	$p' = 6$	$p' = 7$	$p' = 8$
$p = 1$	1	0.9	0.8	0.8	0.9	0.8	0.8	0.3
$p = 2$	0	1	0	0.8	0	0	0	0.4
$p = 3$	0	0	1	0.9	0	0.8	0.8	0.5
$p = 4$	0	0	0	1	0	0	0	0.6
$p = 5$	0	0	0	0	0	0.9	0.9	0.7
$p = 6$	0	0	0	0	0	0	0	0.8
$p = 7$	0	0	0	0	0	0	0	0.9
$p = 8$	0	0	0	0	0	0	0	0

Table A.2. Variable purchasing costs.

Cost	$p = 1$	$p = 2$	$p = 3$	$p = 4$	$p = 5$	$p = 6$	$p = 7$	$p = 8$
PC_{pt}	320	180	205	190	280	188	204	210

Table A.3. Parameters' values of the proposed model.

Parameter	Value	Parameter	Value
T	$1, 2, \cdots, 30$	FC	50000
R	$\subset T$, except 7th day of each week	PC	As Table A.3
P	$\{O^-, O^+, A^-, A^+, B^-, B^+, AB^-, AB^+\} = \{1,2, \ldots, 8\}$	HC_{pi}	25
U	$\{1,2,3\}$	BC_{pt}	$3*pc_{pt}$
I	5, $i \leq 3$ is considered as fresh	EC_p	pc_{pt}
v	200000	ED_{put}	Uniform (15,25)
m_p	450	ND_{put}	Uniform (1,10)
mv_p	25000	C_{pt}	Uniform (100,150)
Demand class	η_{pu}	π_{pu}	$\theta_{pp'u}$ δ_{pu}
u1	0	$0.6*\theta_{pp'3}$	10 10
u2	1	$0.9*\theta_{pp'3}$	7 7
u3	1	As Table A.2	5 5

Table A.4. Products substitution allowance based on medical priorities.

$S^{pp'}$	$p' = 1$	$p' = 2$	$p' = 3$	$p' = 4$	$p' = 5$	$p' = 6$	$p' = 7$	$p' = 8$
$p = 1$	1	1	1	1	1	1	1	1
$p = 2$	0	1	0	1	0	0	0	1
$p = 3$	0	0	1	1	0	0	1	1
$p = 4$	0	0	0	1	0	0	0	1
$p = 5$	0	0	0	0	0	1	1	1
$p = 6$	0	0	0	0	0	0	0	1
$p = 7$	0	0	0	0	0	0	0	1
$p = 8$	0	0	0	0	0	0	0	1

Biographies

Mahnaz Sohrabi obtained her PhD in Industrial Engineering at the Islamic Azad University, Qazvin Branch, Iran, in 2021. She accomplished her MSc in Industrial Engineering in 2014. Her research interests include applied operations research, supply chain modeling, inventory and production planning, project scheduling, and optimization under uncertainty in real-world systems.

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