A Selective Covering-Inventory- Routing problem to the location of bloodmobile to supply stochastic demand of blood

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Abstract

Supplying of blood and blood products is one of the most challenging issues in the healthcare system since blood is as extremely perishable and vital good and donation of blood is a voluntary work. In this paper, we propose a two-stage stochastic selective-covering-inventory-routing (SCIR) model to supply whole blood under uncertainty. Here, set of discrete scenarios are used to display uncertainty in stochastic parameters. Both of the fixed blood center and bloodmobile facilities are considered in this study. We suppose that the number of bloodmobiles is indicated in the first stage before knowing which scenario is occurred. To verify the validation of the presented SCIR model to supply whole blood, we examine the impact of parameters variation on the model outputs and cost function using the CPLEX solver. Also the results of comparison between the stochastic approach and expected value approach are discussed.

Keywords:
Inventory-Routing, Covering problem, Selective Vehicle-Routing, Mobile Blood Collection

1. Introduction

Whole blood and its products are vital for human lives while blood is a special product which supply and demand for it is completely random. The blood supply chain includes the process of collection, production, storage, and distribution blood and its products, from donor to recipient [1]. Since there is no alternative for human blood [2] it is critical to have a seamless process to collect and store this scarce resource. Collection and inventory management are two main activities in the blood supply chain and several studies have been conducted in this field over the years. Figure 1 shows the general various scopes of the research studies regarding supply chain components and decision types (strategic, tactical, and operational), simultaneously.

![Figure 1- various scopes of researches in blood supply chain management](image-url)

In most countries around the world, blood is mostly donated on a voluntary basis so management of blood collection and blood inventory in the fixed or the mobile blood centers in order to preventing shortage in emergency situations is highly important. Mainly, blood collection process is done in the fixed or mobile centers. It is notable that about 80% of all donations are made in bloodmobiles [3] and each bloodmobile represents an investment of $250,000 [4]. Additionally, effective use of bloodmobiles could be helpful in increasing the number of donations [5]. Thus, exact planning for the bloodmobile facilities is particularly important. Determining the right number of bloodmobiles to operate every day; and strategically deploying bloodmobiles to various locations to collect needed blood while minimizing the travelled distance are discussed as important challenges in the literature [6]. In addition, due to the perishable nature of blood, an acceptable inventory policy seeks to maximize demand satisfaction and minimize the amount of blood units that expire [7].
Figure 2- Illustrative example of the proposed model

According to the mentioned reasons, managing blood collection and blood inventory with conflicting objectives especially under stochastic and dynamic condition are one of the problematic issues in the blood supply chain.

In this paper, we present a new two-stage stochastic selective-covering-inventory-routing (SCIR) model to supply whole blood in uncertain environment and manage the inventory level of blood to reduce wastage and holding costs. We study a blood supply network which includes blood center, bloodmobile facilities, and blood donation sites. The rest of the paper is organized as follows: Section 2 presents problem definition and the related literature. Section 3 describes assumptions, indices, decision variables, and mathematical model. Computational results of applying presented model on the generated data sets are discussed in section 4. Finally, the paper is concluded in Section 5.

2. Problem definition and related literature

2.1. Problem definition

We design a new SCIR model to whole blood collection and its inventory management in a blood center during the planning horizon, simultaneously. Periodic stochastic demands could be supplied through collected blood by blood center or bloodmobiles. The bloodmobiles start their tours at the beginning of the planning horizon from blood centers and they do not need to return to the blood center at the end of each period. In this study we suppose that collected blood by each bloodmobile is transferred to the blood center by a vehicle. The stop points for bloodmobiles are selected based on the level of stochastic blood donation in candidate location and also the amount of stochastic blood potential in donation sites in its coverage distance. Each bloodmobile visits only one location in each period and collects blood only from donation sites located within its coverage radius. An illustration of the proposed model is shown in figure 2. Figure 2a, depicts the blood center, the donation sites, and the potential stops of the bloodmobiles and their coverage areas, and figure 2b, shows the covering tours of three bloodmobiles as an illustrative example. In the proposed model, we also consider a policy for inventory management of whole blood under the rules of Iranian Blood Transfusion Organization (IBTO). Based on these rules, at least three days of safety stock must be carried and if the inventory level in each day is less than five days of demand, a special campaign for extra donations begins. To avoid blood spoilage and to reduce the cost of inventory holding, we suppose that blood center could transfer the extra blood inventory to the other blood centers regarding their requirements if and only if its inventory level is more than seven days of demand. To the best of our knowledge, such modeling with these inventory rules considerations in combination of collection process has not been considered in the literatures.

Generally, in this paper following decisions are determined:

- The stopping location of bloodmobiles among candidate locations,
- The covering tour of bloodmobiles,
- The quantity of collected blood by blood center and bloodmobiles,
- The quantity of collected blood by blood campaign,
- And the quantity of transferred blood to the other centers.

2.2. Related literature

Blood supply chain origin dates back to 1960s [8]. Figure 3 illustrates the distribution of the presented papers according to the blood supply chain stages.
To the best of author's knowledge, a wide range of the researches are dedicated to the collection and storage stages. Figure 4 and 5 indicate the trend of studies in the collection and storage according to publication date, respectively. Both of figures reveal the increasing popularity of this subject after year 2000.

In the last decade, there are several comprehensive reviews which analysis the related paper from various aspects in the blood supply chain management such as Beliën and Forcé [9], Lowalekar and Ravichandran [10], and Osorio et al. [11]. The main focus of this section is on the conducted research related to the blood collection and blood inventory management problems associated with our study. Although mobile facilities are widely used for collection of blood donations in many countries including Iran, there are very few studies on bloodmobile operations in the literature. Şahin et al. [11] developed a location-allocation model for regionalization of blood services in a hierarchical network consisting of regional blood centers, blood stations, and mobile facilities. The blood collection problem considering both a fixed site and bloodmobile collection has been addressed by Alfonso et al. [12]. They presented the modeling and simulation of blood collection systems in France. Collection blood through mobile facilities is taken into consideration in recent years. Ghandforoush and Sen [13] presented a nonlinear integer programming model for platelet production and bloodmobile scheduling for a regional blood center to meet daily demand. Fahiminia et al. [14] investigated the emergency supply of blood in disasters. They considered a supply network include fixed and mobile blood center, donation sites, and hospitals with stochastic demands. Although they determined the inventory constrains in their models but they did not forecast the condition which demand exceed capacity of fixed and blood center (as considered in this study). Sahinyazan et al. [5] presented a selective vehicle routing problem suggested by Chao et al. [15] with integrated tours. They optimize the route of bloodmobiles which collect blood and shuttles which transfer collected blood by bloodmobiles to the blood center. They only focused on the optimizing the route of mobile facility with no consideration about blood inventory. Based on Sahinyazan et al. [5] study, Rabbani et al. [16] investigated the mobile blood collection system for platelet production and they optimize the location of bloodmobiles and their routes in two separate models. Gunpinar and Centeno [6] proposed an integer programming approach to the bloodmobile routing problem. They considered uncertainty in blood potentials and applied robust optimization. They also determined minimum and maximum level of blood inventory in each period.

A wide number of papers have reported important approaches to reduce the cost of waste and shortage of blood products [7]. The results of a study conducted in Transfusion Services at Stanford University Medical Center indicated that it is possible to reduce the loss of blood products by 50% if supply chain tools are implemented [17]. Although, most of integrated researches studied storage stage in combination with distribution stage (such as Hemmelmayr et al. [18]; Baesler et al., [7] or production stage (such as Hajjema et al. [19]; Lang and Christian [20]; Ryttilä and Spens, [21]) there is few study in the field of collection and storage, simultaneously. Nahmias [22] studied the inventory ordering policies for perishables including blood bank management. A review paper was reported in Prastacos [23] on the theory and practice of blood inventory management. Baesler et al. [7] created a discrete event simulation model to analyze and propose inventory policies in a blood center. Gunpinar and Centeno [6] focused on reducing wastages and shortages of red blood cells and platelet components of whole blood units at a hospital.

The aim of this study is presenting a new SCIR model to whole blood collection and its inventory management under uncertainty. To the best of our knowledge, a modeling effort for blood supply similar to present study is non-existent.
3. Problem description

Let graph G (V, E) be a geographical network where V is the node of considered network and E represents roads between nodes. In this study, V = {0} ∪ I ∪ L. 0 is the blood center; I = {1, ..., n} is the set of candidate locations for bloodmobiles; and L = {1, ..., m} is the set of potential donor points that must be covered and. Note that collecting of blood from donors are done in both of location indexed by {0}, I, and L but bloodmobile facilities could settle only in special places such as universities or industrial complexes where indexed by I and donors move blood center or bloodmobile location based on their distances to donation (i.e. based on or coverage distance of each blood collection facility: fixed or mobile). Assumption, indices, parameters, and decision variables as well as mathematical formulation of proposed model are described in the following.

Assumptions:
The framework under study considers the following assumptions:

- We use a homogenous fleet of bloodmobiles and do not consider capacity for them.
- The inventory level of blood in the blood center is checked at the end of each period.
- The shortage is not allowed in each period.
- The demand level of whole blood and donated blood (the number of people who are willing to donate blood) in each period is considered stochastic.
- The operation cost of collecting blood in bloodmobile and blood center are not considered in the proposed model.

The indices, parameters, and decision variables to the mathematical model formulation are described as below.

Indices:

- I: Set of candidate locations for bloodmobile indexed by i
- L: Set of potential blood donation sites indexed by l
- T: set of time period indexed by t
- S: set of scenario indexed by s

Parameters:

- $h_i$: Inventory holding cost
- $\lambda$: Cost of call for extra donation
- $\sigma$: Cost of transferring blood unit to the other center
- $c_{ij}$: Distance between bloodmobile location i and j
- $r_{i}$: Distance between bloodmobile location i and donation sites l
- $d_{i}$: Demand of blood center in period t under scenario s
- $\beta$: Percentage of collected units discarded due to a disease detected after testing
- $\alpha$: Percentage of increase in blood donation through blood donation campaign in period t under scenario s.
- $b_i$: Blood potential of blood donation site l.
- $b_j$: Blood potential of blood donation in bloodmobile location j.
- $\tau$: Coverage distance
- $fb$: Fixed cost of establishing a bloodmobile facility
- $M$: A very large number
- $\pi_s$: Probability of scenario s occurrence

Decision variables:

- $I_i$: Inventory level of whole blood at the end of period t under scenario s.
- $BQ_i$: Total unit of collected blood from donors in the blood center in period t under scenario s.
- $CQ_i$: Total unit of received blood to the blood center by bloodmobiles in period t under scenario s.
- $Q^s$: Total unit of received blood to the blood center in period t under scenario s.
- $RQ^s$: Amount unit of extra blood where sent to the other blood centers in period t under scenario s.
- $q_i$: Quantity of collected blood through campaign in period t under scenario s.
- $q_i$: Quantity of collected blood by bloodmobiles in period t under scenario s.
- $p_{it}$: Equals 1 if the donor located in site i refers to blood center for blood donation in period t under scenario s.
- $p_{ij}$: Equals 1 if the donor located in site i referred to bloodmobile k located in site j for blood donation in period t under scenario s.

The objective function and constraints for the proposed model are as (1)-(23):
\[
\begin{align*}
\min z &= f h^* y + \sum_{s=1}^S \sum_{i=1}^T (I^s_i * h + Q^s_i * \lambda + RQ^s_i * \alpha + \sum_{j=0}^n \sum_{t=0}^n c_{ij}^* \times x_{ij}^s)) \\
\text{Subject to:} \\
I^s_i = I^s_{i-1} + Q^s_i - Q^s_i' - d^s_i - RQ^s_{i-1} & \quad \forall s, \forall t \\
Q^s_i = (1 - \beta) q^s_i & \quad \forall s, \forall t \\
q^s_i = \max(0, 5d^s_i, -I^s_i) & \quad \forall s, \forall t \\
Q^s_i = CQ^s_i + BQ^s_i & \quad \forall s, \forall t \\
CQ^s_i = (1 - \beta) q^s_i & \quad \forall s, \forall t \\
q^s_i \leq \sum_{k=1}^m b^s_k \times p^s_{j_k} & \quad \forall s, \forall t \\
BQ^s_i = (1 - \beta) q^s_i & \quad \forall s, \forall t \\
q^s_i = \sum_{j=1}^n \sum_{t=0}^n b^s_k \times x_{ij}^s + \sum_{j=1}^n b^s_k \times p^s_{j_k} \times x_{ij}^s & \quad \forall s, \forall t \\
I^s_i \geq 3 \delta_{-i}^s & \quad \forall s, \forall t \\
RQ^s_i = \max\{(I^s_i - 7d^s_i), 0\} & \quad \forall s, \forall t \\
r^s_j * p^s_{ij} \leq \tau & \quad \forall s, \forall t, \forall l, \forall j \\
q^s_i \leq \tau & \quad \forall s, \forall t, \forall l \\
\sum_{j=1}^m p^s_{ij} + p^s_{ji} \leq 1 & \quad \forall s, \forall t, \forall l \\
\sum_{i=0}^T x_{ij}^s = \sum_{i=0}^T x_{ji}^s & \quad \forall s, \forall t \leq |T| - 1, \forall j \neq 0 \\
\sum_{i=0}^T x_{ij}^s \leq 1 & \quad \forall s, \forall j \neq 0 \\
\sum_{j=0}^T x_{ji}^s \leq 1 & \quad \forall s, \forall i \neq 0 \\
\sum_{i=1}^n x_{ij}^s |Q^s_j| = \sum_{i=1}^n x_{ij}^s Q^i_j & \quad \forall s \\
\sum_{i=0}^T x_{ij}^s = 0 & \quad \forall s \\
\sum_{i=0}^T x_{ij}^s \leq y & \quad \forall s, \forall t \\
I^s_i', Q^s_i', BQ^s_i', CQ^s_i', Q^s_i', RQ^s_i', q^s_i, r^s_j & \geq 0 & \quad \forall s, \forall t \\
x_{ij}^s, p^s_{ij}, p^s_{ji} \in \{0, 1\} & \quad \forall s, \forall t \\
y, q^s_i, q^s_i & \in \mathbb{Z}^+ & \forall s, \forall t \\
\end{align*}
\]

Equation (1) minimizes the total cost function; which includes establishing bloodmobiles, holding cost, cost of blood collection campaign, and transportation cost. Constraint (2) shows the blood inventory level in period \(t\) under scenario \(s\). This level is equal to the inventory level in period \(t-1\), plus total unit of collected by blood center and bloodmobiles in period \(t\) under scenario \(s\), plus total unit of received blood through campaign of blood mobile donation to the blood center in period \(t-1\) under scenario \(s\), minus the stochastic demand in period \(t\), minus amount unit of extra blood where sent to the other blood centers in period \(t-1\) under scenario \(s\). (The inventory level in the end of each period are checked and after that the amount of sending extra blood or supplying shortage blood are determined). Constraint (3) indicates the total units of received blood through blood mobile campaign to the blood center in period \(t\) under scenario \(s\), regarding reduction coefficient \(\beta\). Constraint (4) indicates the campaign for blood collection must be done when the blood inventory level is less than five times the demand. Constraint (5) computes the total unit of received blood to the blood center by itself or through bloodmobiles in period \(t\) under scenario \(s\). Constraint (6) defines total unit of received blood to the blood center by all of bloodmobiles in period \(t\) under scenario \(s\). Constraint (7) calculates the quantity of collected blood units in the blood mobile campaign in period \(t\) under scenario \(s\). Constraint (8) is the total unit of collected blood from donors in the blood center in period \(t\) under scenario \(s\) regarding reduction coefficient \(\beta\). Constraint (9) determines the quantity of collected blood by bloodmobiles in period \(t\) under scenario \(s\). Constraint (10) guarantees that at least three periods (days) of safety stock are considered in blood center. Constraint (11) makes sure that blood transfer to the other centers is possible if only if the blood inventory level in blood center be more than seven times the demand in each period under each scenario. Constraint (12) and Constraint (13) ensure that bloodmobiles and blood center only accept donors within their coverage distance. Constraint (14) imposes that each donor site is served by only blood center or a bloodmobile. Constraint (15) specifies that if there is a bloodmobile coming to node \(j\) on period \(t\) there should be also an outgoing one from node \(j\) on period \(t+1\). Constraint (16) and (17) force that each potential location of bloodmobile under each scenario will be visit utmost one in planning period. Constraint (18) determines that each bloodmobile which starts its tour from center must be back to it in end of its tour. Constraint (19) ensures tours starting from any site other than the blood center. Constraint (20) ensures that the number of used bloodmobiles does not exceed the number of established bloodmobiles. In this model, we suppose that variable \(y\) to determine the number of requirement bloodmobiles independent of each period and each scenario. It is noteworthy that Constraint (3), (16), and (17) together prevent sub-tours of bloodmobiles. Constraints (21)-(23) define the eligible domains of the decisions variables.
4. Computational Results

To evaluate the performance of the proposed model in this study, we generate a set of three numerical examples with small and medium sizes according to the real situation in blood center in Isfahan Blood Transfusion Center. Characteristics of the generated datasets are shown in Table 1. In the present study, after linearizing the model, the GAMS \((23.5)\)– with CPLEX solver is used for optimization.

Table 1. Characteristics of the generated datasets

<table>
<thead>
<tr>
<th>characteristics</th>
<th>Data set 1</th>
<th>Data set 2</th>
<th>Data set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of candidate bloodmobile locations</td>
<td>4</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Number of blood donation sites</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Time period horizon</td>
<td>3</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Number of scenario</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2 shows the numerical results obtained by using GAMS for all of data sets at different reduction percentage \((\beta)\). In Table 2, “Absolute gap” column is difference between MIP solution and best solution obtained using GAMS and also the model runtime is given in the last column. Number of determined bloodmobiles, Average quantity of collected blood by bloodmobiles, blood center, and blood campaign under each scenario are presented for three datasets and varying \(\beta\). We change the value of \(\beta\) between 0.1 and 0.9 in increments of 0.1. By increasing \(\beta\), we observe the number of bloodmobiles as well as cost function increase in three datasets. At a constant level of bloodmobiles in each dataset, first, quantity of collected blood by blood center increase and after that the level of collected blood by bloodmobiles. Finally, if the amounts of periodic demands exceed capacity of blood center and blood mobiles, the needed blood will collect by blood campaign and high costs. The results indicate that the proposed SCIR model produces the expected output correctly. Although, for some instances which the absolute gap is large, a solution approach to solve them would be more useful. In this study, also the benefit of the two-stage stochastic programming approach is examined by comparing its performance against that of an expected value approach. In this paper, we used stochastic parameters under discrete scenarios for demand and amount of potential blood in donation sites and bloodmobiles locations in each period. There are several measures to evaluate the benefit of scenario based approaches. Value of the Stochastic Solution \((VSS)\) introduced by Birge [24] is one of the common criteria to investigate the benefits of the two-stage stochastic programming approach.

VSS can be formulated as:

\[
VSS = z_{EEV} - z_{HN}
\]

Where \(z_{EEV}\) and \(z_{HN}\) indicate the objective values under expected value and stochastic programming approaches, respectively. \(z_{HN}\) is the optimal objective value of the presented in section 3. To compute \(z_{EEV}\), the presented model is solved by replacing the values of the stochastic parameters with their expected values. The solution obtained from solving this model provides the optimal number of bloodmobiles \((y)\) for the expected value approach. In the final step, initial model is solved based on each scenario, separately while the number of bloodmobiles are fixed to the optimal number of bloodmobiles \((y)\) obtained in the previous step. Based on the computed results, VSS for data set 1 for all of \(\beta\) values are equal 0, since there are only 2 scenarios in data set 1 and occurrence of scenarios are equal, so there is no difference between stochastic and expected value approach. Figure (6) and (7) indicate the trend of VSS over a range of \(\beta\) for data set 1 and 2, respectively. The results show that trend of VSS is completely depends on value of \(\beta\) and is not regular regarding increasing \(\beta\). In data set 1, for \(\beta\) values more than 0.7, not only the stochastic programming approach is not useful but also VSS value is negative. Note that in higher level of \(\beta\), the majority of blood demand supply by blood campaigns so considering stochastic value for blood potential in donation sites could not improve cost function. No difference observed between stochastic or deterministic approaches when \(\beta\) equals 0.1 or 0.2. In the range of 0.3 to 0.7 for \(\beta\) values, the proposed stochastic programming approach has a higher priority than the expected value approach. The obtained results show that trend of VSS for data set 2 follow similar pattern to those of data set 1, with some of the differences. Generally, the stochastic programming approach does not show a clear preference over an expected value approach and depends directly on the \(\beta\) value in both data sets.
Table 3. The impact of varying reduction percentage ($\beta$) on cost function and optimal number of blood facilities, collected blood by bloodmobiles, centers, and campaign

<table>
<thead>
<tr>
<th>Data set</th>
<th>$\beta$</th>
<th>Cost function (MIP solution)</th>
<th>Number of used blood mobile</th>
<th>Average quantity of collected blood by bloodmobiles in each scenario</th>
<th>Average quantity of collected blood by blood center in each scenario</th>
<th>Average quantity of collected blood by blood campaign in each scenario</th>
<th>Absolute gap</th>
<th>Solution time ($)</th>
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5. Conclusion

The timely Supply of safe blood is as challenging issues in the healthcare problems. This work presents a selective-covering- inventory- routing (SCIR) model for supply stochastic demand of whole blood under uncertainty conditions. In the presented two-stage stochastic approach, the number of needed bloodmobiles was determined in the first stage before knowing information about occurrence of the scenarios and other decisions were made in the second stage. In our model we considered the inventory management rules of Iranian Blood Transfusion Organization (IBTO) as well as the bloodmobile routing problem. Three randomized datasets were generated and sensitivity analysis was done based on model parameters. Numerical results showed that the small instances of the problem could be solved to optimality using GAMS in reasonable amount of time but a solution approach to solving the big instances was needed. Results showed the collected blood by blood center, bloodmobiles and campaign increase, respectively when demand and reduction percentage of blood increasing. Also, we
investigated the benefit of stochastic value approach versus expected value approach by using VSS criteria. Results showed that the stochastic programming approach does not show a clear preference over an expected value approach and depends directly on the $\beta$ value in each data set.

References


