

Multi-level network planning for blood supply for critical conditions

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Abstract

In this paper, blood supply chain management has been considered for critical conditions. The supply chain problem considered the unique features of blood such as its perishability, availability only from human resources, limited supply of blood for transfusion treatments and uncertainty. To solve this problem, a mixed integer programming model was developed with the aim of minimizing costs incurred by shortage and wastage. The proposed model was solved by the optimization software GAMS and to demonstrate effectiveness of the model, numerical samples were presented according to information received from the Tehran Blood Transfusion Center to determine accuracy and efficiency of the model. Sensitivity analysis was conducted on key parameters of the model (risk of damage to hospitals, demand and capacity) that analyze the factors applied to the model. Given that the optimum value of the model was taken as a balance between shortage cost and waste cost (by adding two units to the blood center capacity, results showed that supply chain cost was reduced by 45%), taking into account the existing problems in the area, consistent with the real world, this model investigated the planning and management of a blood supply chain in critical conditions by determining how to meet the hospital's needs.

Keywords

Inventory management, network blood supply, critical conditions, and blood crisis management.

Introduction

As a product, blood is perishable, scarce and valuable. It has a key role in protecting and saving lives. Blood can only be produced by humans and currently there is no chemical alternative product (Gunpinar and Centeno 2015). Hence, management of blood supply requires precise monitoring in terms of collection, storage and distribution as well as appropriate use of blood and its products once it has been received from donors. The management of blood and blood products is a problem of general interest with a number of complicating aspects (Haijema, van der Wal et al. 2007) and experts have identified five general key features for the purposes of supplying critical aid in the form of blood products (Gralla, Goentzel et al. 2014). These features include amount of aid provision, priorities according to product type, location, speed, and cost of implementation. Integration of these features presents an understanding of the importance of an overall approach to the concept of humanitarian aid supply chain management, (such as the blood supply chain) (Fahimnia, Jabbarzadeh et al. 2015).

Blood is usually taken from people as "whole blood", and then mechanical isolation can be done in a laboratory at a later stage to produce its other useful components. These components are used in hospitals after confirmation that a blood sample is healthy and identification of blood type in order to meet the demand for a particular type of blood. A "whole blood" unit can be divided into five blood products: red blood cells (RBCs), plasma, white blood cells, serum and platelets. Red blood cell (RBC), as the most abundant cell type in the blood contains a protein called hemoglobin that carries oxygen in our cells. The antigens contained in red blood cells are divided into four main types and can be transmitted to a patient with a similar blood type. Plasma is a yellow liquid obtained by removing RBCs from whole blood. This component is also divided into four types based on its antibodies and can be transmitted to a patient with the same blood type. White blood cells are part of the immune system that defend the body against infectious agents. Serum is without a coagulation factor and does not constitute white and red blood cells. Finally, platelets have a coagulation factor, available in plasma and are related to the body's coagulation such that they enable tissue regeneration in cases of a wound or bleeding. Platelets can also be drawn directly from the human body through use of an apheresis device. All other blood components, except for plasma can become outdated. In particular, since platelets can be stored for only 5 to 7 days, they are considered highly perishable. The second most highly perishable blood component is RBC, which can be stored up for 42 days under certain conditions.

Blood service operations in each country are an important and integral part of the national health care system (Şahin, Süral et al. 2007). So like any other supply chain, a blood supply chain has specific components. It begins with blood from a donor. Blood is taken from a donor in blood centers and mobile blood bases and then, on completion of the required tests to ensure health of the blood supply and determination of blood type, blood units are then sent from blood centers to hospitals. Hospitals are considered as demand points, and determination of decision variables such as the amount of blood maintenance, allocation to hospitals by blood centers and determination of amount of blood allocated to each hospital have been done determined according to consideration of the features of blood, particularly its perishability. However, there has been an increasing number of natural and man-made disasters that have prompted an increase in research on blood supply chain management in the fields of science, business and government (Ransikarbum and Mason 2016). According to the World Disasters Report (2015) by the International Federation of Red Cross and Red Crescent (IFRC), about 6311 such events were reported in the years 2005 to 2014, such that there were 0.8 million retaliations, 1.9 billion affected people, and 1.62 trillion dollars of damage. This significantly high rate of mortality and loss confirms the need for more research on disaster management and related issues. Considering the perishability of blood components, a hospital order for more blood than is needed is problematic because aging blood has deficiencies and this loss of quality can contribute to death of patients. Also, this increase in disaster events increases the need for blood and its products in crisis conditions, so production systems should be designed and managed efficiently to enable a quick response in the event of a crisis due to features of perishability and supply limitations (Rivera-Gómez, Gharbi et al. 2016). Hence, management of blood products has become an important issue in recent years for hospitals and related institutions. Although advances in technology in recent years, have solved many problems, the need for blood and blood donors and management of the supply chain is still an issue that requires more attention. This paper has been organized as follows. In Section 2, there is a discussion of the relevant literature. Formulation of the model is presented in section 3. Numerical and analytical results of the model are discussed in Section 4. A review of this paper is presented in the Section 5 and finally, according to the contents contained in Section 6; there are suggestions for future research.

2. Literature review

The aim of the blood supply chain is supplying adequate safe blood to hospitals. It is paramount that blood is available at hospitals for transfusion purposes since a shortage may endanger the life of patients. In the blood supply chain, replenishment in the blood bank is not fully in control of the decision makers, since replenishment occurs by blood donations (Hosseinifard and Abbasi 2016). Until the early 1960s, all items had an infinite life span and immutable functionality. The literature highlights that inventory models assumed that items could be stored for an unlimited duration (Nahmias 2011). While certain types of product are in decline or have become obsolete in a certain period and are thus unstable (Goyal and Giri 2001). Since management of perishable inventory systems (such as blood products) has a cost for society (in terms of life and economic costs), it has gradually received more research attention (Kouki and Jouini 2015).

This research is generally related to supply chain management of perishable items and specific research on blood products as perishable items was started in the 1960s by Zyl (Janssen, Claus et al. 2016). The paper written by Nahmias in 1984 focused on inventory of perishable produce and provides a brief overview of models suitable for application in blood bank management (Nahmias 1982). In 1984 Prastacos presented an overview of the theory and practice of blood supply management (Prastacos 1984). Since then, there have been nearly one hundred published articles corresponding to blood. Two peaks are visible in the history of published articles of blood products (Beliën and Forcé 2012); one in the period between 1976 and 1985 and more recently between 2001 and 2010.

Issues on supply chain for blood products have been analyzed using a wide range of methodologies. In particular, simulation methodology ([9]-[19]); mathematical proofs and derivations ([20]-[23]), dynamic programming ([11], [24]) and integer programming ([25]-[29]) are commonly cited in the literature. These methods have been used either alone or in combination with other methods to analyze and solve real-life problems. Other studies have been done as follows; deterministic demand ([20], [22], [26], [29]-[32]); stochastic demand ([9]-[15], [17], [18], [21], [24]-[26], [33]-[36]), and these can be classified in relation to individual hospitals ([10]- [12], [18], [24], [34],[36]-[41]) and regional blood centers ([11], [12],[15], [17],[18],[25], [26], [29], [33]-[36], [40], [42]-[44]). Furthermore, models have incorporated different characteristics of a blood supply chain and made indications of a variety of decision variables, objective functions and constraints (Gunpinar and Centeno 2015).

Events of 11 September 2001 prompted the America Blood Community to assess response measures to tragic events and to develop strategies to deal with domestic disaster and possible terrorist attack events. In December 2001, the America Association of Blood Banks (AABB) held a meeting with representatives of organizations of blood banks, blood collectors and hospital providers and government agencies to address these concerns (Handbook 2008).

Author	Summary	Pro (+)/Con(-)
Brodheim, Derman) (et al. 1975	Inventory model based on average age and average waste using Markov chain approach	-Assumption: shelf life 21 days
Cohen and) (Pierskalla 1979	FIFO system delivers lowest wastage. Model based on EOQ theory trading off wastage against shortage	+ Seminal work - Limited sample size due to limited computing capacity +Results can be statistically verified
(Nahmias 1982)	Review of perishable inventory theory Classifies models into fixed and random lifetime	+ Proves that FIFO is very hard to achieve in reality + Approximations are more fruitful than exact calculations
Goyal and Giri) (2001	Review on inventory models for perishable goods Categorized goods into random and fixed lifetime	+ Seminal work -Blood inventory management
(Lin, Tan et al. 2000)	Model with time-varying demand, deterioration, equal review periods, and a fixed planning horizon	+ Many similarities with blood supply chain - Allows backlogs
Van Donselaar, van) (Woensel et al. 2006	Compared different approaches with how supermarkets Manage perishable goods using automated store ordering systems	+ Many similarities to blood supply chain +Main strength is the simplicity
Van Dijk, Haijema) (et al. 2009	Target stock level model for platelet production based on real data from a Dutch blood bank	+ Verification of findings + Reduction of time expiry by 15% to 20%
(Gunpinar and Centeno 2015)	Three integer programming models in blood supply chain	+ considering lifetime of blood products

Table 1 – An overview of articles related to the topic under discussion

On December 26, 2003, an earthquake of 6.6 on the Richter scale destroyed the city of Bam in southern Iran. More than 30,000 people were killed and wounded, and 85% of the buildings were completely destroyed or severely damaged (Eshghi and Zare 2003). Abolghasemi et al., (2008) reviewed preparedness for blood transfusion considering the response of the blood center

during the Bam earthquake in 2003. The report stated that, despite short term increase in blood donations, there were problems with aspects of blood transfusion that needed more research such as; (1) necessity of a mass appeal for donations; (2) the long-term impact of the disaster on blood supply; (3) safety of donated blood; (4) rate of discarded collection and its impact on peoples' attitudes; and (5) first-time donor return rates (Abolghasemi, Radfar et al. 2008).

The 2003 earthquake in Bam caused more than 29000 deaths and left 23000 injured. A total of 108985 units of blood were donated, but only 21347 units (23%) were distributed in hospitals across the country. Kerman province, the site of the disaster, received 1231 units (13%) of units of donated blood in the first four days after the disaster. The Bam experience revealed crucial missteps in development of a post-event strategy for blood product management. This led to development of a detailed disaster preparedness and response plan to address the issues of donation, distribution, communication, transportation and coordination (Abolghasemi, Radfar et al. 2008). Since reports have highlighted that the past decade has seen an increase in disasters and numbers of people affected by disasters, and considering the vital importance of blood supply, the issue of blood and blood supply chain management is a critical issue (Nagurney, Masoumi et al. 2012).

Each year, all countries of the world are faced with economic crises due to natural or man-made disasters (Baghersad and Zobel 2015). Iran is not an exception, and each year, it is exposed to natural and man-made hazards. According to the World report on disaster risk reduction published in 2009, the level of threat in Iran only against natural hazards is estimated to contribute to the death of about 106 thousand people in four decades, an estimated 8 out of 10 (UNHCR 2009). In addition to damage to the general population and infrastructure, a disaster also has an effect on service delivery systems. In particular, the structural and non-structural and functional components of a hospital can be affected by hazards and disasters and, in addition to physical consequences to staff and patients, and damage to property and equipment, loss of performance for admission of victims (Ardalan 2011).

According to the contents presented in Table 1 showing the articles related to the present issue by presenting the topic of each article and their strengths and weaknesses.

2.1 Contributions in the literature

In addition to developments reported above, the blood supply chain can be developed further. There is a gap in the literature on models that include age of a blood unit. Also, most models have not made a distinction between required and donated blood types. In addition, structural destruction in critical conditions is not observed as a contributing factor in the models. This study presents a mixed integer programming model that explicitly takes into account age of blood units and separates the four main blood types (four different products in terms of patients' needs), in accordance with the conditions of hospitals (centers that required blood) that are well developed at the time of an accident.

3. Description of the problem and formulation of the model

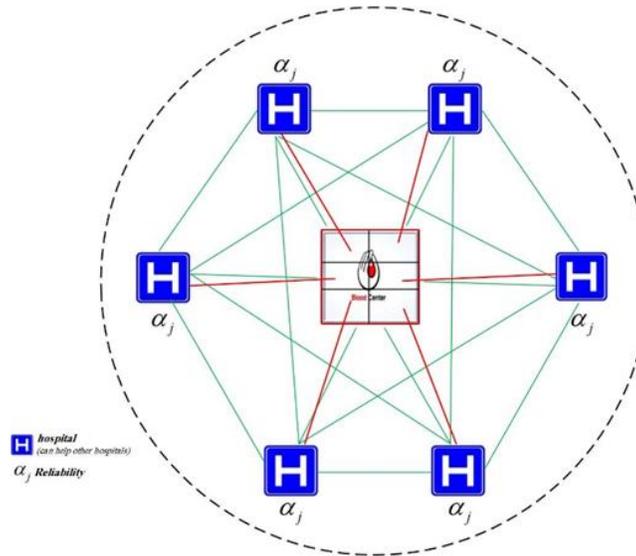
The present model plans a multi-level network planning for blood supply in critical conditions, which includes a blood center and several hospitals. In general, the relationship between a blood center and each hospital is as follows:

The hospital orders blood to meet its demand for daily operations to the Blood Center therefore; the optimum blood level for a specific period should be defined.

Hospital j provides its required blood by receiving a daily amount of blood from a blood center. Blood has a limited lifespan and a blood center transfers a blood unit at age i with a certain probability to hospital j without any time delay that, this probability for blood unit with higher i (older blood) is more than a blood unit with a lower i (younger blood). A hospital stores the received blood units according to blood type and takes into account the age of each blood unit. Depending on the needs of patients, a hospital's stock of blood fulfills the blood requirement according to FIFO policy; this means that older blood (i) should be used earlier than younger blood ($i-1$). If i days old blood unit (i is the age of the blood unit) is used by the end of a day then it will be out of the cycle, but if it is not used, by the next day it is considered as a blood unit ($i+1$) in the calculations (blood unit's age will be $i+1$). A blood unit could be used until the end of its life. As a result, three destinies are possible for each blood unit:

1. An i days old blood unit is used before the end of its life-time and is used to meet the needs of a hospital.
2. An i days old blood unit is not consumed until the end of its life, in which case it should be removed from the cycle. In this case, the cost of wastage occurs.
3. An i days old blood unit is not consumed at the end of the time period t to meet the needs of a hospital but is still usable (the life time of i days old blood unit is not over). In this case, the blood unit is transferred to the next period as inventory. Considerations are added to the network in a critical condition, which is considered by the coefficient as usability in a hospital in a critical condition, which is called the probability of destruction of a hospital in a critical situation.

In the case of a critical event, in addition to the issue of an increased number of applicants requiring blood units, it is possible that a hospital j has been destroyed and is unusable. It should be noted that in the event of a critical condition, the inventory of a hospital could be used to meet the needs of other hospitals faced with shortages.



3.1 Formation of the Model

In this model, the purpose was to minimize the total cost of the network by determining the optimal number of blood units ordered from blood type g by hospital j to the blood center at the beginning of the time period (t). Model assumptions were as follows:

1. The blood center's capacity for hospital j is limited.
 2. Lead times for blood supply are zero (hospital j receives the blood unit ordered to the blood center without delay).
 3. Red blood cells have a limited lifetime of 42 days; this period includes also the time taken for blood safety diagnostic tests at the blood center (2 days are required for blood safety diagnostic tests).
 4. Age of the blood units received from the blood center has been specified and can be from 3 to 42 days.
 5. The hospital policy general provision when a doctor requests blood for a patient, is FIFO.
 6. If the demand is not satisfied due to unavailability of blood units, then a shortage cost is incurred.
 7. If blood units expire, there is a wastage cost associated with discarding blood units.
 8. Hospital j provides blood to meet the shortage of hospital j' with blood of age of less than I .
 9. There are four blood types and each type may only be used for a patient with same blood type.
- Tables 2-4 summarize the indices, the parameters and the variables that are used in the models.

Table 2: Indices for Models

i :	age of blood unit $i = 1, 2, \dots, I$ (days)
t :	time period $t = 1, 2, \dots, T$ (days)
g :	Blood type (1: A, 2: B, 3: AB, 4: O)
j :	Hospital $j = 1, 2, \dots, J$
j' :	the hospital with shortage of blood units

Table 3: Parameters for Models

I :	lifetime of blood unit
T :	length of the planning horizon
J :	Number of hospitals
c :	Cost of blood preparation and transportation to the hospital
b :	Unit shortage cost of blood (lost sales) at the hospital
h :	Unit holding cost of blood at the hospital
w :	Unit wastage cost of blood at the hospital
θ_{git} :	Proportion of i days old blood unit in the blood shipments from blood center for blood type g in time period t , $0 \leq \theta_{git} \leq 1, \sum_{i=3}^I \theta_{git} = 1 \quad \forall t, g$
d_{gt}^j :	Demand for blood unit of the blood type g in time period t at the hospital j
CAP_{gt}^j :	Capacity of the blood center (allocated to the hospital j) for blood type g in time period t
f :	Cost of transportation of a blood unit from a hospital to another hospital
α_t^j :	The probability of destruction of the hospital j at the time t (when a disaster occurs) $\sum_{t=1}^T \alpha_t^j = 1 - \alpha_0^j \quad \forall j$

Table 4: Decision Variables for Models

m_{git}^j :	Auxiliary variables associated with i days old blood unit of the blood type g at time t in excess of hospital j . If all the available blood in the hospital j is not completely used to meet the demand of the same period, this variable shows the number of blood units in an age type transferred to next period.
$r_{gt}^{j'}$:	Number of blood shortage for blood type g at the end of time t at the hospital j'
u_{gt}^j :	Number of blood wastage of blood type g at the end of time t at hospital j
v_{git}^j :	Inventory level of i days blood unit of blood type g at the end of time t at the hospital j
x_{gt}^j :	Number of blood ordered of blood type g by hospital j to the blood center at the beginning time of t
y_{git}^j :	The number of i days old blood unit of blood type g received by hospital j at the beginning of time t
z_{git}^j :	(1) if i days old blood unit of blood type g is used to satisfy the demand in period t at hospital j , (0) otherwise.
$tr_{git}^{j'}$:	i days old blood unit of blood type g in the period t , transferred from the hospital j to the hospital j' .

$$\begin{aligned}
 \text{Min } & c * \sum_{j=1}^4 \sum_{g=1}^4 \sum_{t=1}^T x_{gt}^j + \left(\sum_{j=1}^4 \sum_{g=1}^4 \sum_{t=1}^T h * v_{git}^j + \sum_{j=1}^4 \sum_{g=1}^4 \sum_{t=1}^T w * u_{gt}^j + \sum_{j=1}^4 \sum_{g=1}^4 \sum_{t=1}^T b * r_{gt}^{j'} \right) + \\
 & \left(\sum_{j=1}^4 \sum_{g=1}^4 \sum_{t=1}^T \alpha_t^j * w * v_{git}^j \right) + \left(\sum_{j=1}^4 \sum_{j' < j} \sum_{g=1}^4 \sum_{t=1}^T f * tr_{git}^{j'} \right) \quad (1)
 \end{aligned}$$

S.T

$$x_{gt}^j \leq CAP_{gt}^j \quad \forall j, g, t \quad (2)$$

$$y_{git}^j = 0 \quad i = 1, 2, \forall j, g, t \quad (3)$$

$$\begin{aligned}
 y_{git}^j &= x_{gt}^j * \theta_{git} & i = 3, \dots, I, \forall j, g, t \\
 x_{gt}^j &= \sum_{i=3}^I y_{git}^j & i = 3, \dots, I, \forall j, g, t
 \end{aligned} \quad (4)$$

$$z_{git}^j \geq z_{g(i-1)t}^j \quad i = 3, \dots, I, \forall j, g, t \quad (5)$$

$$d_{gt}^j = \sum_{i=3}^I \left(v_{g(i-1)(t-1)}^j + y_{git}^j \right) z_{git}^j - m_{git}^j + \sum_{j'} \sum_{i=3}^I (tr_{git}^{j'} - tr_{git}^{i'j'}) \quad \forall j, g, t \quad (6)$$

$$\left(z_{git}^j - z_{g(i-1)t}^j\right)\left(v_{g(i-1)t}^j + y_{git}^j\right) \geq m_{git}^j \quad i = 3, \dots, I, \forall j, g, t \quad (7)$$

$$z_{git}^j = 0 \quad i = 1, 2, \forall j, g, t \quad (8)$$

$$d_{gt}^j - \sum_{i=3}^I \left(v_{g(i-1)(t-1)}^j + y_{git}^j\right) \leq r_{gt}^{j'} \quad \forall j, g, t \quad (9)$$

$$v_{git}^j = \left(1 - z_{git}^j\right)\left(v_{g(i-1)(t-1)}^j + y_{git}^j\right) + \left(z_{git}^j - z_{g(i-1)t}^j\right)m_{git}^j \quad i = 3, \dots, I, \forall j, g, t \quad (10)$$

$$v_{git}^j = 0 \quad i = 1, 2, \forall j, g, t \quad (11)$$

$$v_{gi(0)}^j = 0 \quad \forall j, g, i \quad (12)$$

$$u_{gt}^j = v_{g(t)}^j \quad \forall j, g, t \quad (13)$$

$$\sum_{j=1}^J \sum_{i=3}^I tr_{git}^{jj'} \leq r_{gt}^{j'} \quad \forall j', g, t \quad (14)$$

$$x_{gt}^j \in \mathbb{Z}^+ \quad \forall j, g, t \quad (15)$$

$$r_{gt}^j, u_{gt}^j \in \mathbb{Z}^+ \quad \forall j, g, t \quad (16)$$

$$y_{git}^j \in \mathbb{Z}^+ \quad \forall i, j, g, t \quad (17)$$

$$m_{git}^j, v_{gt}^j \in \mathbb{Z}^+ \quad \forall i, j, g, t \quad (18)$$

$$z_{gt}^j \in \{0, 1\} \quad \forall i, j, g, t \quad (19)$$

$$tr_{git}^{jj'} \in \{0, 1\} \quad \forall j, j', i, g, t \quad (20)$$

The objective function (1): seeks to minimize the cost of blood preparation and the expected inventory, wastage and shortage costs during the planning horizon for all hospital with considering the blood types and the wastage costs of the destructed hospital in the day that a disaster occurs and the cost of providing shortage of hospitals through other hospitals. Constraint (2) is capacity constraint of the blood for each hospital with considering the blood type (supplier). Constraint (3) ensures that the hospitals never receive one or two days old blood units from the blood center as two days are required for testing after the blood is collected. Constraint (4) allocates blood units to each age type for each hospital with considering the blood type. Constraint (5) guarantees the FIFO blood issuing policy in each hospital for all blood types. Constraint (6) requires demand to be fully satisfied when blood supply exceeds demand for all hospitals with considering the blood type. Otherwise, a hospital or more hospitals face a shortage issue. Constraint (7) assures that the values of auxiliary variable, m_{git}^j , do not exceed the number of blood units available in their age groups in each hospital with considering the blood type. Constraint (8) ensures that two days old blood units are not used to satisfy the demand as the hospital only receives blood units older than two days old from the blood center. Constraint (6) and Constraint (9) capture the number of blood shortages of each hospital in with considering the blood type. Constraint (10) updates end period blood inventory levels for each age group in each hospital with considering the blood type. Constraint (11) assures two days old blood is never available on inventory of any hospital. Constraint (12) states that there is no inventory available in any hospital at the beginning of the analysis period. Constraint (13) identifies the wastage levels of the hospital at the end of each period for each hospital with considering the blood type. Constraint (14) ensures that transferred blood unit is not higher than the shortage. Constraints (15) -(18) shows $x_{gt}^j, r_{gt}^j, u_{gt}^j, y_{git}^j, m_{git}^j, v_{gt}^j$, are non-negative discrete variables since the blood units are received in blood bags. Constraint (19) and constraint (20) states that $z_{gt}^j, tr_{git}^{jj'}$ are binary variables.

Due to the interactions between binary and discrete variables, the optimization problem includes non-linear terms in the above formulation. After the first linearization technique is applied which is detailed in Appendix, the interactions between v, y, m

and z variables in constraints (6), (7) and (10) are replaced with the corresponding linearization variables from which constraints (21) -(23) are obtained. In addition, constraints in appendix are added into the new formulation.

$$d_{gt}^j = \sum_{i=3}^I (\gamma_{git}^j + \phi_{git}^j - m_{git}^j) + r_{gt}^j + \sum_{j'} \sum_{i=3}^I (tr_{git}^{jj'} - tr_{git}^{j'j}) \quad \forall g, j, t \quad (21)$$

$$\gamma_{git}^j + \phi_{git}^j - \mu_{g(i-1)t}^j - \psi_{git}^j \geq m_{git}^j \quad i = 3, 4, \dots, I, \forall g, j, t \quad (22)$$

$$v_{git}^j = v_{g(i-1)(t-1)}^j + y_{git}^j - \gamma_{git}^j - \phi_{git}^j + \lambda_{git}^j - \delta_{git}^j \quad i = 3, 4, \dots, I, \quad \forall g, j, t \quad (23)$$

4. Sensitivity Analysis

The model considered is programmed in the software GAMS and solver CPLEX and run in the system with specifications CORE™ 2 Duo CPU and RAM 8GB. A continuation of change in trends of critical parameters is shown on the objective function.

4.1 Data

Table 5 summarizes the values of cost parameters that are used in our models. Most of the cost parameters are obtained from the literature as shown in (Gunpinar and Centeno 2015). Holding cost was obtained from real data from a Regional Medical Center (RMC). Transportation cost from blood Center and from a hospital to another hospital were obtained from estimation of Tehran blood Center.

Table 5: Cost Parameters

Parameters	values	Units
b	1500	\$/unit
c	250	\$/unit
h	1.25	\$/unit*day
w	150	\$/unit
f	100	\$/unit

Table 6: Variation range of Parameters

Parameters	variation range
j	1, ..., 6
i	3, ..., 20
g	1, ..., 4
t	1, ..., 7
α_i^j	uniform(0,0.2)
CAP_{gt}^j	8
d_{gt}^j	round(uniform(5,10))

Table 6 summarizes the variation range of parameters that are used in our model.

4.2 Variations of α

Variations of α show its effectiveness at the cost of the objective function. If a hospital is damaged in a critical condition and some or all of its resources cannot be used, then the hospital's inventory at that time will be considered under wastage cost. The higher probability of destruction or damage of a hospital according to the amount on a hospital's inventory, the amount of wastage cost then the cost of the objective function will increase.

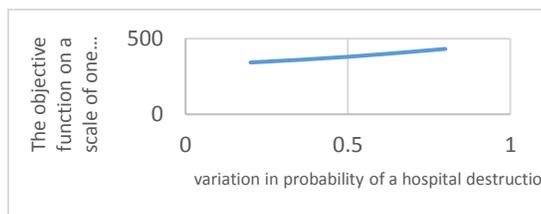
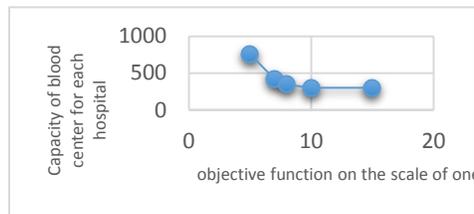


Figure 4.2 – variation of objective function in terms of variation of probability of hospital destruction.

As can be seen in Figure 4.2 when the probability of hospital destruction is 0.2, the cost is about below 350 that, with an increase of this probability to 0.8, the cost reaches more than 400 (just for one hospital).

4.3 Demand and Capacity

The best case is when capacity meets all demands and the worst case is when the capacity of a blood center is at its minimum. This important issue is obtained in Figure 4.3. As can be seen when the capacity of a blood center to meet the hospital's needs is at the lowest level then the cost is at its highest level, here higher than 750, and the increased hospital capacity reduces the costs including the cost of shortages, and the objective function decreases. But it continues until there is no increase in wastage costs. As we can see, capacity of more than 15 units for each hospital of each blood type has no impact on cost reduction.



units for each hospital of each blood type has no impact on cost reduction.

Figure 4.3 – objective function in terms of change in the capacity assigned to each hospital.

As can be seen in Figure 4.4, an addition of two units to a blood center's capacity decreases the supply chain costs by 45 percent. The reduction in costs will continue with increased capacity until the capacity is equal to or more than the hospital demand, in which case the minimum cost of objective function is achieved.

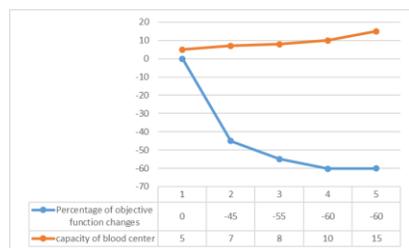


Figure 4.4 – The percentage of cost function changes

4.4 Solution time of the model

If the design scale becomes larger, because many factors must be considered in the model, then the time taken to solve the model in GAMS software increases exponentially. This can be seen in Figure 4.5. With an increasing number of periods studied in the model, the problem-solving time is increased significantly.

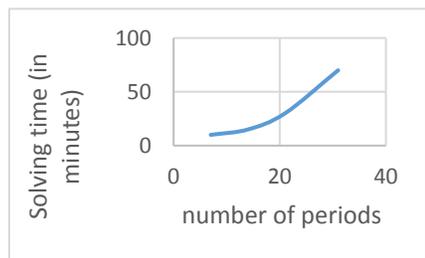


Figure 4.5 – Solving the time proportional to the number of periods

5. Discussion

Blood and blood products, as a valuable and life-giving commodity, are perishable by nature and there is no alternative product, so in terms of supply chain management remains an important and controversial issue. Provision of this product by donors and the demand for blood products by hospitals are concerns that are always subject to uncertainty and this increases complexity of the supply chain. Since shortage of a blood product can cost lives as well as excess inventory due to its limited lifetime and associated cost of wastage, precise and optimal planning for the blood supply chain is important and necessary. The problems of this chain become most apparent in critical conditions such as in a natural disaster. According to discussions in the literature, the likelihood of a natural disaster around the world increases each year, such that an effective blood supply chain has become increasingly important. This study has attempted to take a step, however small, to improve blood supply chain planning. A model has been provided in accordance with the literature to discover weaknesses in the previous research and to consider the issues that have been overlooked in previous papers.

6. Conclusion and opportunities for future research

In this paper, an optimization model has been developed for hospitals to manage blood resources more efficiently such that, ultimately, costs can be reduced and services improved for patients in the hospital. The focus of this article was on red blood cells with low lifetime, which are scarce products among blood components. The model was formulated explicitly by taking into account the age of blood and blood type and hospital in a critical condition. In addition, in the end, the effects of some factors such as percentage of damage during an incident in the hospital and blood center capacity levels were analyzed. The obtained results are useful for executive managers of hospitals and will help in the process of determining orders that will minimize shortages, wastage and reduce the total cost.

6.1 Future Suggestions

Since this supply chain is a complex, yet important chain, it is always in need of improvement. In the following, a number of suggestions are presented that can be effective.

- In the proposed model, hospital priorities are considered the same. Prioritization can be considered for hospitals to supply shortages with higher priority.
- In the proposed model, each blood type could only belong to the same blood type for simplifying calculations but in real-life, some blood types can also be assigned to two or three other blood types.
- This model can be studied on a large scale with a meta-heuristic method to present a situation that corresponds more closely to the real world.

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Appendix: First Linearization Technique

The first linearization technique is focused on the interactions between binary and discrete variables and assigns new discrete variables to replace the products of interacting variables. As in (FICO™ Xpress Optimization Suite), y is called the linearization variable and reflects the products of x and d in the linearization process where x is a discrete variable and d is a binary variable. Lower bound and upper bound of x are assumed to be known and take the values of L and U respectively. Then, integer programming formulation after linearization process is as follows:

$$Ld \leq y \leq Ud$$

$$L(1-d) \leq (x-y) \leq U(1-d)$$

To linearize our models, linearization technique mentioned above is applied to the non-linear terms and the interactions between binary variable z and discrete variables v , y and m in the original formulation are replaced with their products (called linearization variables) as shown below. Furthermore, the following constraints (that are numbered) are added into the new formulation.

M: big M

$$z_{git}^{(j)} v_{g(i-1)(t-1)}^{(j)} = \gamma_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t$$

$$\gamma_{git}^{(j)} \leq z_{git}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \quad (1)$$

$$\gamma_{git}^{(j)} \leq v_{g(i-1)(t-1)}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (2)$$

$$\gamma_{git}^{(j)} \geq M \cdot (z_{git}^{(j)} - 1) + v_{g(i-1)(t-1)}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (3)$$

$$z_{git}^{(j)} y_{git}^{(j)} = \phi_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t$$

$$\phi_{git}^{(j)} \leq z_{git}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \quad (4)$$

$$\phi_{git}^{(j)} \leq y_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (5)$$

$$\phi_{git}^{(j)} \geq M \cdot (z_{git}^{(j)} - 1) + y_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (6)$$

$$z_{git}^{(j)} m_{git}^{(j)} = \lambda_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t$$

$$\lambda_{git}^{(j)} \leq z_{git}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \quad (7)$$

$$\lambda_{git}^{(j)} \leq m_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (8)$$

$$\gamma_{git}^{(j)} \geq M \cdot (z_{git}^{(j)} - 1) + m_{g(i)(t)}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (9)$$

$$z_{g(i-1)t}^{(j)} m_{git}^{(j)} = \delta_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t$$

$$\delta_{git}^{(j)} \leq z_{g(i-1)t}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \quad (10)$$

$$\delta_{git}^{(j)} \leq m_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (11)$$

$$\delta_{git}^{(j)} \geq M \cdot (z_{g(i-1)t}^{(j)} - 1) + m_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (12)$$

$$\begin{aligned} z_{g(i-1)t}^{(j)} y_{git}^{(j)} &= \psi_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \\ \psi_{git}^{(j)} &\leq z_{g(i-1)t}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \end{aligned} \quad (13)$$

$$\psi_{git}^{(j)} \leq y_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (14)$$

$$\psi_{git}^{(j)} \geq M \cdot (z_{g(i-1)t}^{(j)} - 1) + y_{git}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (15)$$

$$\begin{aligned} z_{g(i-1)t}^{(j)} v_{g(i-1)(t-1)}^{(j)} &= \mu_{g(i-1)t}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \\ \mu_{g(i-1)t}^{(j)} &\leq z_{g(i-1)t}^{(j)} \cdot M \quad i = 3, 4, \dots, I, \forall g, j, t \end{aligned} \quad (16)$$

$$\mu_{g(i-1)t}^{(j)} \leq v_{g(i-1)(t-1)}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (17)$$

$$\mu_{g(i-1)t}^{(j)} \geq M \cdot (z_{g(i-1)t}^{(j)} - 1) + v_{g(i-1)(t-1)}^{(j)} \quad i = 3, 4, \dots, I, \forall g, j, t \quad (18)$$

$$\begin{aligned} \gamma_{git}^{(j)}, \phi_{git}^{(j)}, \psi_{git}^{(j)}, \mu_{g(i-1)t}^{(j)}, \lambda_{git}^{(j)}, \delta_{git}^{(j)} &\in \mathbb{Z}^+ \\ i &= 3, 4, \dots, I, \forall g, j, t \end{aligned} \quad (19)$$

As both stochastic and deterministic models indicate nonlinear terms with the same interacting variables (for example, v and z), in order to save some space, we show their linearization in one formulation and differentiate them using (j) at the top corner of the variables.

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