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A Computer Simulation Analysis of Blood Bank Inventory Policies*

by

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ABSTRACT

A detailed model of a hospital blood bank inventory system is developed. The effects on the overall performance of the system of several alternative inventory control policies are analyzed by means of digital computer simulation. The performance of the system is evaluated in terms of three measures of effectiveness: blood shortage, blood outdating and operating cost.

This study confirms previous findings that the operating cost of the blood bank can be minimized by: (1) operating at the optimal inventory level and, (2) reducing as much as possible the number of days blood spends in the assigned inventory. It is also shown that sophisticated ordering policies do not give better results than the simple ordering policy commonly used by most blood banks' managers. Finally, perhaps the most important result of the study is that the optimal inventory level is apparently independent of the time blood spends in assigned status.

Demand for blood is so rapidly increasing all over the world that it becomes more and more difficult to meet it by simply trying to find new donors or inducing current donors to contribute more. The major reason for not being able to rely exclusively on these traditional policies is that new medical techniques requiring larger quantities of blood and blood derivatives are being introduced much faster than rates of growth among potential donors aged 18-65 from whom donors are drawn [14]. This situation has prompted a more critical view of the efficiency of the decision policies governing hospital blood bank management. More specifically, attention has been drawn to the high percentage of blood lost because of outdating. However, if appropriate management policies are not followed, efforts to reduce outdating may cause excessive shortages at the blood bank. These shortages must then be made up through emergency shipments or emergency donor calls often at a high penalty cost. Of course, the cost of an outdated unit is also high because of the loss of processing time and supplies, possible procurement costs, and most importantly the loss of the unit's potential to fill a demand for blood. It is this balance of costs, excessive outdates and potential shortages that is addressed in this paper.

In the last two decades, a growing number of researchers have addressed themselves to the problem of helping the blood bank manager find better ways of controlling his blood inventory. One important approach to the problem was in the complete automatization of the record keeping of all operations of the blood bank [5, 9]. Another major approach was to focus on the problem of finding the best policies with regard to controlling the blood bank inventories. Along this line, various models of either single hospitals [4, 6, 7, 8, 10, 11, 13] or groups of hospitals [2, 8] have been constructed in order to examine the comparative merits of alternative decision policies. While the first models were based on rule of thumb procedures [6], later models have been more analytical and have used absorbing Markov chain theory [10] and the theory of perishable inventory [11]. Finally, because of the large complexity of the process, several authors have developed simulation techniques [4, 7, 8, 13]. Since a recent review of these models is available in Elston [3], they will not be further detailed here.

Two limitations of the above models can be noted. First, with few exceptions [11], these models do not deal with the problem of determining the optimal ordering, issuing and release policies. Another common weakness is that they generally fail to distinguish between "assigned" and "unassigned" inventories. As a result, these models underestimate the amounts of shortage and outdating and alter the amount of blood ordered. The works by Jennings [7, 8] and Rabinowitz [13] are noticeable exceptions to this trend.

In contrast to the literature cited, the overall objective of the study reported here was to determine what are the optimal ordering, release and issuing policies. This objective was achieved by first simulating on a digital computer the inventory system of a particular hospital blood bank and then by performing an optimization search.

PRESENTATION OF THE MODEL

As indicated earlier, the model involves two kinds of inventories: an unassigned inventory which contains the blood available to meet any physician's request and an assigned inventory which consists of blood crossmatched and reserved for a particular patient, that is, blood which has been demanded by the patient's doctor.

The flow of blood is as follows: blood is removed from the unassigned inventory - when doctors request blood to be crossmatched, when blood is outdated and when it is shipped to other hospitals according to the Central Blood Bank request. Blood is added to the unassigned inventory - when ordered blood arrives from the Central Blood Bank, when blood is released from the assigned inventory and when blood is drawn from (often randomly arriving) donors. The assigned inventory is depleted by blood usage (transfusion), by the release of blood demanded but not used, and by outdating and it is replenished by blood requested by physicians.

Depending upon the ordering policy chosen, an order is placed with the Central Blood Bank in the morning and is received a couple of hours later. It must be noted that the model focuses on routine operations and does not take into account any scheduled uses of fresh blood (e.g., open heart surgery).

The basic structure of the model is conveniently presented in Fig. 1. A detailed description of the model can be found in Pinson [12].

Fig. 1: The Hospital Blood Bank Inventory Model

CRITERIA OF PERFORMANCE

We recall that the basic purpose of the study was to compare the relative effectiveness of various alternative policies and then to find which ones are optimal. The three criteria which were used to measure the performance of the blood banking system under each alternative policy were

1) the amount of blood shortage, 2) the amount of blood outdated, and 3) the operating costs of the blood bank. The first two criteria are the most commonly found in the literature. In addition, a fourth criteria was considered, namely the age of blood transfused which is viewed as an index of quality rather than a measure of performance as long as it stays at "acceptable" levels.

To find the optimal inventory level, we found it helpful to define the following loss function L(S) in terms of shortage and outdates:

$$L(S) = 55 \times A(S) + 25 \times B(S)$$

or

$$L(S) = 35 \times A(S) + 25 \times B(S)$$

where A(S) is the daily amount of short units and B(S) is the daily amount of outdated units. Following Bodily [1], the cost of one short unit was set either at $55 or $35 depending on whether the emergency orders come from frozen blood or fresh blood. Also, the cost incurred by one outdated unit was considered to be the processing cost, i.e., $25.

POLICIES EXAMINED

In this section, the particular ordering, release and issuing policies considered in the study will be presented.

1. Ordering Policy: The aim of the manager is to maintain a buffer stock not too large in order to avoid outdates, not too small in order to avoid shortages. The ordering policy depends on the number of unassigned blood units available. Let x_i be the number of unassigned blood units in the class of age $i = 1, \ldots, 21$. Let $X = (X_1, \ldots, X_{21})$ represent the state of the unassigned inventory. Y(X), the total amount to be ordered, is equal to:

$$Y(x) = \max\left(0,\ a_0 S - \sum_{i=1}^{21} a_i x_i\right)$$

where S is a preassigned inventory level, a_0 is a constant and a_i are some weighting factors.

The present research dealt with the two following policies:

Policy I: $a_i = 1$, $i = 0,\ldots, 21$ which is the policy most often used in practice.

Policy II: $a_i = .5 + (21 - i) \times 0.05$, $i = 1,\ldots, 21$; $a_0 = 1$. Under this weighting system, the amount of blood ordered is greater when unassigned blood is older and about to expire than when blood is younger and has a longer shelf life.

2. Release Policy: Let λ be the number of days the blood is kept in the assigned inventory. The present study dealt with the effects of $\lambda = 1, 2, 3, 4$ on the performances of the blood bank ($\lambda = 2$ is the most commonly used policy in the blood banks interviewed in this study).

3. Issuing Policy: It was decided that the issuing policy for removing blood from the unassigned to the assigned inventory would be of the FIFO (First In - First Out) type. This policy was chosen because, as proven by Pierskalla and Roach [11] for $\lambda = 0$ and by our first simulation runs for $\lambda > 0$, it minimizes both shortage and outdating.

COLLECTION AND STATISTICAL ANALYSIS OF DATA

Data used in this study were collected at the Hospital Blood Bank of Evanston, Illinois. Some other information was also obtained from data made available by the North Suburban Blood Center (Glenview, Illinois).

Since no transfusions are made between blood types, it was assumed that the eight ABO-Rh types of blood are wholly independent of each other. To limit the scope of the study, only the data relative to the most common type, namely type O^+, were analyzed (this type is believed to represent 39%

of the total blood). However, the model should apply equally well to all eight types of blood, because the nature of the optimal policies will not change, only their magnitudes change.

Whenever possible, quantities that are unpredictable by blood bank managers have been characterized by probability distributions rather than deterministic values. Probability distributions were then defined for the age of incoming blood, for the daily amount of blood requested by physicians, for the percentages of blood transfused (depending on the value of the demand), for the daily amount of blood given by random donors and for the amount of blood returned to the Central Blood Bank.

SIMULATION OF THE MODEL

To avoid oversimplification, the model was left in a form too complex to permit an analytical study. The model was therefore simulated on a computer over a period of 300 days. After a time-series analysis of the mean and variance of the outputs of the simulation, it was found that 200 days were necessary to allow the system to stabilize. Consequently, the results of the last 100 days will be reported.

In addition to the so-called face validity, the internal validity (or reliability) of the model was checked by trying a number of runs with all parameters and initial values held constant but with different strings of random input variables. It was found that the average variation in shortage and outdates was around 10% which was considered reasonable.

ANALYSIS OF THE RESULTS

Effects of different levels of the preassigned inventory: The performances of the blood bank were measured for four values of the preassigned inventory level, namely S = 10, 20, 30, 40 blood units. Since shortage and outdating are linked together, the results are presented in Fig. 2. The percentages outdating and short are computed respectively as percentages of the total usage (transfusion plus outdating) and the total demand.

Fig. 2: Shortage-Outdating Characteristic (for $\lambda = 2$ and ordering Policy I)

As S increases, the outdates rise slowly whereas the short units drop very sharply. This gives a very small slope to the curve. We may note that the general shape of the curve is in agreement with Jennings' findings [7].

The Shortage-Outdating curve, which represents a trade off between the amount of short and outdated units can help the blood bank manager to choose a certain inventory level depending on how he is willing to weight shortage vs. outdating.

For both of the shortage cost functions described earlier, the loss function behaves as shown in Fig. 3. Since the function seems convex, a Fibonacci search was performed to minimize the function. The optimal inventory level was found to be $S_0 = 31$ units. The point $S_0 = 31$ is also where the average shortage goes to zero. In addition, a sensitivity analysis was performed on the loss function. It was found that within one or two units around the minimum S_0, $L(S)$ is hardly sensitive (variation of only 6%). But, if S moves away from the minimum, $L(S)$ increases very rapidly. The conclusion that can be drawn from these findings is that the blood bank manager should choose his inventory level close to the minimum if he wants to optimize the effectiveness of the blood banking operations. A deviation from this value will drastically drop the performances of the blood bank.

Cost per short unit = \$55

Curve I = Ordering Policy I

Curve II = Ordering Policy II

Fig. 3: Loss Function Curve (for $\lambda = 2$)

Effects of the two different ordering policies: As stated previously, we are interested in the performances of the blood bank under either Policy I (when the unassigned inventory is less than S, the difference is ordered) or Policy II (ordering more blood when the unassigned inventory is older). The simulation was run for each of these two policies alternatively with $S = 10, 20, 30, 40$ and $\lambda = 1, 2, 3, 4$. We found that Ordering Policy II generates less outdating than Ordering Policy I, but not as much as might have been expected. The difference is principally clear for large values of S. At $S = 40$, Policy II leads to .14% less outdating than Policy I, but near the optimal level S_0, the decrease is only 4%. Since the shortage tends to go in the other direction, one cannot conclude that one policy is better than the other in terms of shortage and outdating. For both policies, the loss function behaves very much in the same way (see Fig. 3). The cost is slightly higher if Policy II is chosen when S is less than S_0 and slightly lower when S becomes greater than S_0. But around the minimum, the difference is only 1% to 2%. Thus, giving more weight to younger blood does not seem to improve the effectiveness of the blood bank as much as one might have thought. In conclusion, it appears that the common policy where all blood are weighted equally is as good as the more complex one and much simpler to implement and understand.

Effects of different values of λ (number of days blood is kept in the assigned inventory): The major cause of outdating in an hospital blood bank is the existence of blood cycles from unassigned to assigned inventory and back again to unassigned inventory. As mentioned earlier, the effect of the existence of an assigned inventory have generally been ignored in previous models (see Jennings [7], [8], and Rabinowitz [13] for exceptions).

As expected, when λ increases, the amount of outdated units increases sharply while the amount of short units does not seem to be affected. For example, at the optimal value S_0, outdates increase from 11 units (2.7%) to 107 units (22%) and shortage stays close to zero. These variations result in a vertical shift in the Shortage-Outdating Curve and in the loss function curve as shown in Fig. 4. An important finding of this simulation is that the value of the optimal inventory level S_0 is reasonably independent of λ and stays around 30 units. More sensitivity analysis was undertaken to verify this finding. The simulation was run for several different distributions of the input variables (blood demand, age of incoming blood) and for λ varying up to 7 days. Again, it was found that S_0 stays within the range 25-35 units. This result strengthens our first finding.

Fig. 4: Loss function Curve (for Ordering Policy I)

Two major conclusions may be drawn from these results. The first is that λ has to be kept as small as possible to minimize the cost of operation of the blood bank. However, λ is often bounded by administrative feasibilities. Due to the length of some medical and surgical needs, sometimes λ cannot be equal to 1 or even 2 days. The second major conclusion is the fact that S_0 seems to be independent of the values of λ. This result is extremely important for blood bank researchers because analytical blood bank inventory models, so far, have been developed under the assumptions of $\lambda = 0$, i.e. no assigned inventory. To incorporate the variable λ considerably increases the analytical complexity of the models. Therefore, if the optimal inventory level is independent of λ, the optimal analytical solution found under the condition $\lambda = 0$ could be extended to the case of $\lambda \neq 0$.

SUMMARY AND CONCLUSIONS

The findings of this simulation and optimization study can be summarized as follows: 1) whenever possible, the blood bank should be operated close to the optimal inventory level in order to maximize its effectiveness, 2) the simple ordering policy commonly used by blood bank managers seems to be as good as the one in which more blood is ordered when the unassigned inventory is older, 3) as far as is administratively feasible, blood bank managers should attempt to achieve an outdating gain by reducing the time blood units spend in assigned inventory, and 4) the optimal inventory level seems to be independent of the time blood stays in the assigned status - a finding which is important for researchers working on blood bank analytical models.

The study reported here can be considered as a basis for further investigations of blood bank inventory control. More precisely, the present model could be extended by considering 1) 2 orders per day, 2) a multiple crossmatching process (see Rabinowitz [13]), 3) the utilization of frozen blood for emergency shipments, and 4) a demand for varying degrees of freshness of blood.

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