# SIMULATION OF BLOOD BANK SYSTEMS*

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The inventory systems associated with blood banking are characterized by a number of features which make them particularly interesting and challenging to analyze. In addition to the perishability of blood and its derivative products, we note that both supply and demand are stochastic processes. The only source of supply is the human donor, and their use in whole or component form is indicated by a variety of medical transfusion procedures. While demands for blood and its many derivative products occur at hospital and transfusion locations (TLs), their storage and distribution involve a multi-echelon inventory network.

The major responsibility of all blood centers is to administer the collection, processing, storage, and distribution of whole blood and blood products in a manner which insures that all blood-related demands are met. In addition to this primary goal, each center is concerned with the minimization of wastage through outdates, the maintenance of high-quality standards, and the reduction of shortages which require either emergency shipments from other blood banks, emergency donor appeals, or the delay of non-emergency and elective medical procedures.

In this paper, we consider the use of simulation to develop decision procedures for the management of individual hospital blood banks (HBBs) and large central blood bank systems (CBB). Simulation was used because this comples stochastic multi-product multi-echelon perishable inventory problem is intractable by analytic techniques.

The application of simulation to the analysis of blood bank inventory problems has led to recognition of the following issues for the use of simulation in health care systems analysis.

    1.  The need for the development of generally applicable decision rules as opposed to the use of a model to generate outputs associated with

specific system configuration.

2. The requirement to quantify the trade-off between "efficiency" and "quality" in health care delivery. In the context of blood banks, this multiple goal analysis problem led to the requirement that the model estimate the impact of blood bank inventory decisions on outdates, a measure of efficiency, and shortage of blood products, which is directly related to the quality of health care.

3. The need to recognize those factors which are present in health systems which are subject to managerial control, and those factors which must be viewed as structural or environmental constraints. In the context of blood bank inventories, this issue involved identification of the impacts of medical decisions and practices on the part of the blood bank director and physicians requesting blood products for their patients.

The paper is organized as follows: in the next section, the hospital blood bank logistics simulation model is described. The following sections consider inputs and input analysis, validation, output analysis, decision function estimation, conclusions from the use of the model, and conclusions for the applicability of simulation to health care systems analysis.

## Hospital Blood Bank Structure

In an HBB, blood supply can be of any age between fresh and the maximum of 21 days, and is obtained from a variety of sources (see Figure 1). Blood is consumed by transfusion into patients and those untransfused units which reach the age of 21 days are removed from the inventory (outdated). The process of issuing blood for transfusion involves the intermediate step of crossmatching

whereby samples of the unit to be transfused and the patient's blood are com-
bined and tested for an adverse physiological reaction. If the unit tests out
to be compatible with the patient's blood, then the unit is assigned in advance
of transfusion to the particular patient in question. This procedure gives rise
to a two level inventory structure of assigned and unassigned inventory. Matters
are complicated further by feedback between the two inventory levels since phy-
sicians, wishing to avoid procedural delays, tend to over order by about a factor
or two. The unused, crossmatched units are eventually returned from the assigned
to the unassigned inventory after a delay of a number of days. This delay time
(which may or may not be controllable by the blood bank director) will be denoted
by the variable $\lambda$.

It is clear that when supply is of varying ages and when stock is returned
then one can observe inventory at the unassigned level to be of all ages between
fresh and 21 days. The differentiation of blood by age leads to an issuing se-
quencing decision on the part of the HBB director. Attention is usually restricted
to policies of issuing the oldest available units first or the youngest available
units first. When all supply is fresh, these policies reduce to FIFO (first-in-
first-out) and LIFO (last-in-first-out) issuing respectively. The logistical
structure of the hospital blood bank inventory is summarized by the set of con-
trolling decisions and material flows illustrated in Figure 1. The simulation
model of this system is described in [1, 6].

Central Blood Banking System

A community blood bank inventory system is characterized by a network of
blood banks serving a specified geographical region. The managerial control of
the network is exercised or coordinated through a central facility. Figure 2
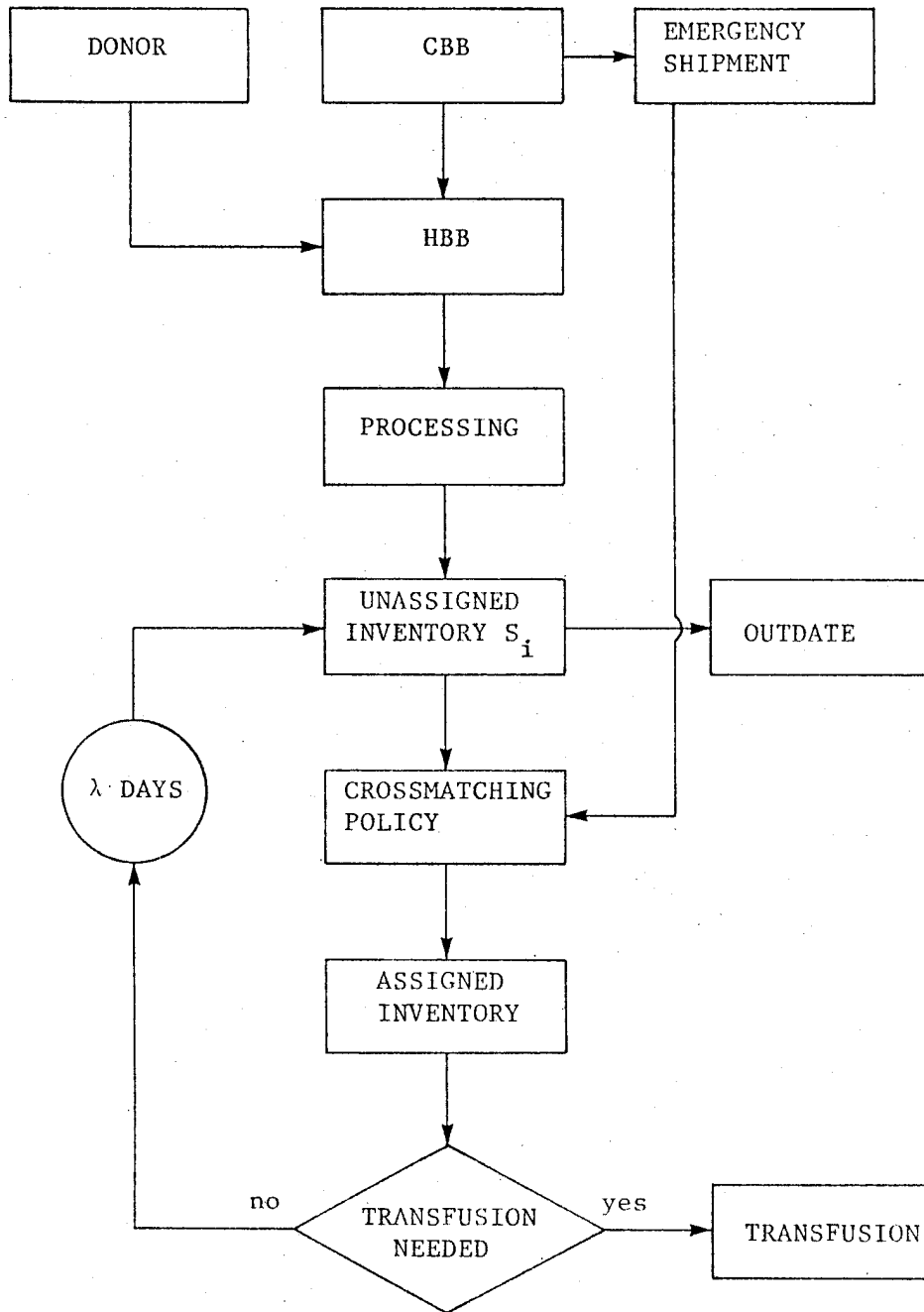
FIGURE 1

FLOW CHART OF A BLOOD UNIT

IN A HOSPITAL BLOOD BANK

OTHER CENTRAL
OR REGIONAL
BLOOD BANKS

CENTRAL
BLOOD
BANK

(CBB)

DONORS
a. Assurance Plan
b. Replacement
c. Altruistic
d. Paid
e. Other

PROCESSING

EMERGENCY
SHIPMENT

CBB INVENTORY

$S_0$

Recycle
Policy of
CBB

OUTDATES

ALLOCATION
POLICY OF
CBB

TRANSSHIP-
MENT POLICY
OF CBB

TRANSFUSION
LOCATION #1

$S_1$

TRANSFUSION
LOCATION #2

$S_2$

TRANSFUSION
LOCATION #N

$S_N$

UNASSIGNED
INVENTORY
at TL #1

ASSIGNED
INVENTORY
at TL #1

UNASSIGNED
INVENTORY
at TL #2

ASSIGNED
INVENTORY
at TL #2

UNASSIGNED
INVENTORY
at TL #N

ASSIGNED
INVENTORY
at TL #N

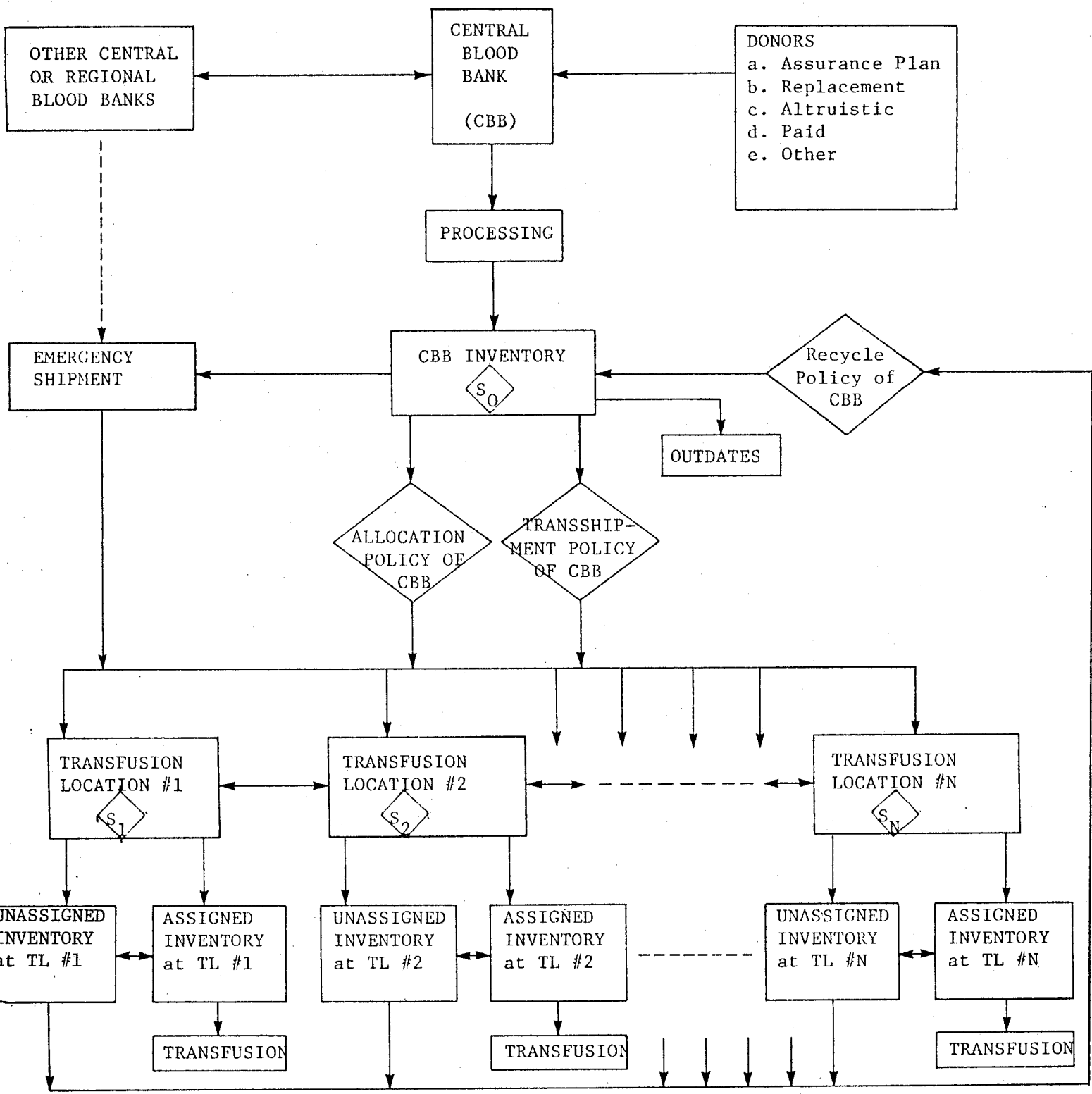TRANSFUSION

TRANSFUSION

TRANSFUSION

FIGURE 2

FLOW CHART FOR A CENTRAL BLOOD BANKING SYSTEM
SHOWING INVENTORY LOCATIONS AND CBB DECISION POLICIES

is a schematic drawing of the inputs, outputs, and flows in a centralized system. Some of the decisions needed by the CBB are shown in the diamond-shaped boxes. The variables $S_o$, $S_1$, . . ., $S_N$ represent the vectors of units of each blood component needed on hand each day at the CBB and at the TLs in order to meet the system needs without excess outdates.

In addition to the decisions needed for the HBB, the CBB must consider routine and emergency shipments to each TL, transshipments among TLs, allocation of its own stock to the TLs when their demands exceed available supply and re-cycling of old units to high probability users to avoid outdates in the system.

An important factor of a central system is the degree to which inventory decisions are made in a centralized or decentralized manner. Although there are certain obvious benefits to a centralized system due to economies of scale of operations, reduction in randomness of both supply and demand, dissemination of teaching and research findings and quality control and reliability through more uniform practices and procedures, there may be a few disadvantages. It is pos-sible to realize some diseconomies of scale due to increases in donor services, phlebotomy, administrative, transportation, and information costs. The simula-tion model of this system is described in [ 7 ].

## Simulation Inputs

The simulation models require specification of input factors relating to system environment and control policy. The factors considered include: para-meters to specify the daily demand process, parameters to specify the age (of units supplied) process, the transfusion fraction, order-up-to level, issuing policy, recycle delay parameter $\lambda$, shortage cost, outdate cost and travel distance.

The collection of data for the estimation of parameters associated with

various distributions mentioned above, involved a detailed analysis of log books
and inventory record files from a variety of blood bank sources. We note that
the choice of input models which have parameters which are a) easy to interpret
and b) taken from data which is easy to collect, simplified the process of anal-
ysis and validation significantly. Substantial input from various blood bank
managers was necessary to conceptualize the inputs of this analysis.

## Simulation Outputs

Model outputs include a detailed record of all inventory transactions and
the trajectory of the age distributions of both assigned and unassigned inven-
tories characterized by the input and decision parameters. For the purposes of
decision making, the objective was to minimize average daily shortage plus out-
date costs. Thus a key output is the cumulative record of total outdates and
shortages.

The simulation models were run to ascertain the cost minimizing inventory
levels and their relationships to a broad range of exogenous environmental fac-
tors. Accordingly, a Fibonacci search routine was used to identify the optimal
inventory levels. The procedure involved multiple runs of the simulation models
for a fixed set of input parameter values and fixed supply and demand realiza-
tions in which the inventory levels were varied.

The analysis indicated a surprising stability on the part of optimal inven-
tory levels to changes in the blood banking system. The results of a five-factor
experimental design     led to the estimation of an ordering rule relating
optimal inventory levels to a number of key factors associated with the blood
bank environment [ 2 , 7 ].

These results are shown in Table 1 using a log-linear decision rule for
an individual TL. Similar outputs have been computed for CBB's and their
satellite TLs.

TABLE 1

### Blood Decision Rule All Variables (Log-Linear)

| Variable | Coefficient | Statistical Error | t-Value |
|---|---|---|---|
| $\ln(d_M)$ | 0.7604 | 0.00972 | 78.24 |
| $\ln(p)$ | 0.1216 | 0.02925 | 4.16 |
| $\ln(\lambda)$ | -0.0677 | 0.01791 | -3.78 |
| $\ln(A)$ | -0.0138 | 0.01128 | -1.22 |
| $\ln(C_S)$ | 0.0520 | 0.04485 | 1.16 |

Intercept        1.61248

Regression                                    Error

| | | | | |
|---|---|---|---|---|
| Degrees of Freedom | 5 | | Degrees of Freedom | 90 |
| Sum of Squares | 60.72035 | | Sum of Squares | 0.88765 |
| Mean Square | 12.14407 | | Mean Square | 0.00986 |

S.E. of Estimate        0.09931

F-Value        1231.3

Multiple R-Squared        98.56

where

$d_M$ is the mean daily demand for a blood type;

p is the average transfusion to crossmatch ratio;

$\lambda$ is the crossmatch release period;

A is the average age of supply; and

$C_S$ is the unit shortage cost.

Other outputs such as probabilities of shortages and outdates given input and decision parameters and optimal decisions for crossmatch release, issuing, allocation recycling and transshipment were also obtained. All of these and other outputs from the simulation models were then incorporated into a large scale analytic transportation-location-allocation model and a large scale donor recruitment-allocation model for a region.

## Validation

Since the primary output measures were long term averages, it was necessary to verify that our estimates had converged to their steady state values. Tests of speed of convergence and sensitivity to run length were thus carried out. The variance of output measures was established by altering the random number seed and replicating the simulation.

Internal validity or reliability of the model was established by a detailed analysis of the various model outputs for a large number of input parameter configurations. Literally hundreds of different configurations were ultimately run, and it was therefore possible to establish internal consistency with a high degree of confidence. Face validity, or acceptability of the model by experts has been established by presenting the results of the model to many audiences of blood bank directors. The actual representativeness has been established by comparing the model against published results of actual blood bank operations.

As a final verification we are currently using the model as a predictive instrument to evaluate the potential benefits and costs of extending the lifetime of blood, which is now legally defined to be twenty-one days, to thirty-five days by the use of a new additive, adenine. The model will predict the impact on outdates and shortages under various assumptions of managerial control when the blood lifetime is extended. These results will ultimately be checked against the results of a national survey which is being conducted to evaluate the before and after effects of this new additive.

## Final Comments About the Use of Simulation

o Health care simulation studies must be carried out in the context
of the policy issues facing the health care systems. For the case
of blood banks, the overriding concern was efficient use of the
blood resource. There was documented evidence to suggest that
there was excessive outdating and shortages due to improper sched-
uling and poor management. The blood bank community now recommends
policies based on managerial conclusions which have come out of the
study [ 3 ].

o As in all modelling exercises, the ultimate decision is what should
be modeled and at what level should it be modeled. In the blood
bank situation, it was necessary to focus on the key factors which
could be variable with managerial decisions and which were relevant
to their policy concerns. Initially we over-specified the level of
detail needed to achieve the desired outputs. The result was
excessive running time.

o Our analysis is an example of a recursive statistics-optimization-
simulation approach to system modeling. The advantage of this
approach is that it capitalizes on the best features of these
methods while minimizing the disadvantages of each method used
alone. In the recursive approach, the simulation models are
used to deal with complex system details. The optimization step
used the simulation model to evaluate the cost of different decis-
ions and to ultimately select optimal inventory levels for a
specific system configuration. Statistical techniques are used
to analyze the real data inputs, the simulation generated outputs
and to estimate relationships between optimal decisions and exog-
enous system parameters. These relationships were then used in
an optimization model which examined resource allocations, dis-
tribution policy, location and capacity for a regional blood bank
system [4, 5].

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