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Administrative Report

An Overview of a Hierarchy of Planning Models for Regional Blood Bank Management

M. A. COHEN, W. P. PIERSKALLA, R. J. SASSETTI AND J. CONSOLO

From the University of Pennsylvania, Philadelphia, Pennsylvania, Northwestern University, Rush-Presbyterian-St. Luke's Medical Center and the Chicago Regional Blood Program, Chicago, Illinois

Optimal regionalization of a blood banking system requires a hierarchical structure based on an analysis of preexisting elements in the region to determine at what level of activity economies of scale, cost effectiveness and efficiency will be greatest. We have applied operations research techniques to segments of the blood service complex. This paper is an overview of the general results of this research. From analysis of the data in each segment, a mathematical response function is developed for such managerial processes as demand forecasting, requirements computation, crossmatch and recycle control at each level of the hierarchy in a regional system. These processes in independent hospital blood banks are contrasted with those in hospital blood banks and transfusion services which are dependent on central blood banks for their supply. An example is presented of a model which is useful in the planning of a regional system. Implementation of these hierarchical models in hospital blood banks can reduce outdating, size of inventories and shortage. In central blood banks, these models can minimize shipment quantities, determine optimal transshipments and the most efficient routing.

THE NATIONAL BLOOD POLICY proposed that steps be taken to provide a supply of blood adequate to meet the needs of all citizens, that the supply should be of the highest possible quality, easily accessible to all segments of our society and that the system providing this blood should do it in the most efficient manner possible.[6] It has become widely recognized that to accomplish the goals of this National Blood Policy, regionalization of blood banking services must occur in some form. Fundamental to the concept of regionalization is the belief that the national system can best be achieved by building on the existing strengths of the present system in such a way that the continuity of essential services will not be jeopardized.[1] In order to make meaningful and effective changes, it is necessary to understand the functional interrelationships of the various components of the blood service complex. Further, as knowledge is gained about these interrelationships, steps can be taken to make these systems operate in a more effective and efficient manner.

The blood banking community and others, cognizant of the constantly limited supply relative to the ever increasing demand for blood, have applied various techniques to maximize its utilization.[13] In the past decade, much effort has been expended to analyze both the practical methods for inventory control and the function of independent hospital blood banks and central or community blood banks and the transfusion services which they serve. Most, if not all of this work, was directed at the problem of finding policies which result in the most effective trade-off between outdating and shortages, antithetical factors central to the question of efficiency of operation.[8,10]

It is the purpose of this paper to review the results of this extensive research effort in the area of blood bank management. Particular emphasis will be placed on the analysis carried out by the authors in the Chicago area.[4,5,9,15] This particular effort was directed

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toward analyzing comprehensive managerial policies for blood bank systems ranging from local hospital transfusion services to regional blood centers. The concept of regionalization for the multiple echelons (levels) of blood bank services was defined and the effect of regionalization on recommended managerial practices was considered. An attempt is made to synthesize some significant findings into a hierarchy of mathematical models which describe operations, permit decision making and forecasting at an operational level and meaningful planning for a regional system.

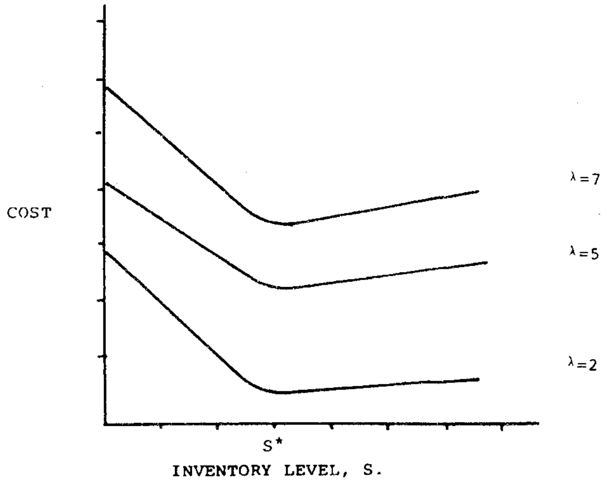

FIG. 1. Shortage/outdate cost versus inventory level. S* is the optimal inventory level; λ is the crossmatch-recycle time in days.

In order to apply operations research techniques, the initial step required is the observation of the system under consideration. This has a two-fold character; one is the analysis of the operation of the system and the development of a concept of the flow of its processes and their relationships. The other is the acquisition of quantitative data relating to each of the processes being described. From the analysis of the system, a single critical process can be selected and within that process, the single most important factor can be determined. For example, in blood banking, the process may be inventory control or transportation. The critical factor may be the actual inventory level of each blood type or, in the case of transportation, the routing. The next step is a statistical analysis of each class of data acquired for the various processes in order to determine their statistical distribution and to make parameter estimates. The next step may involve the application of some methodology such as multivariate regression analysis techniques to arrive at a mathematical function describing the critical process selected in terms of variables representing other relevant processes. Having arrived at a mathematical function which describes a process in terms of several variables, it is now necessary to test the variables for their contribution to measures of performance for the critical process and reduce the number of arguments of this function to include only those variables which have been shown to contribute significantly. It is then necessary to use this derived function with simulated or real data to generate tables or curves of the values of performance measures for the single critical process relative to any one or several of the variables included in the function. Since the models are designed to determine the trade-off between two or more antithetical factors, the functions generated are often convex (U shaped) with respect to the variables considered. The optimal trade-off occurs at the point where the response function has a minimum at some value of the variable or variables (Fig. 1). Using these curves or tables, a manager can select the optimal value for the critical process and determine at what level the various contributory processes must operate in order to achieve it.

Hospital Blood Bank

In the hierarchy of blood banking, the hospital blood bank or transfusion service is the first echelon at which management techniques can be applied to modulate the supply and its attendant costs in response to a demand which is not controllable by "management." The director of the hospital blood bank has five areas which require the

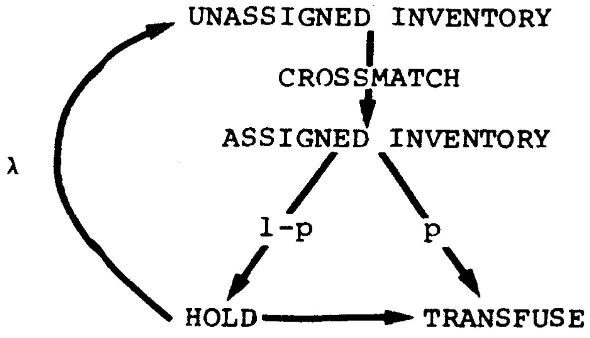

FIG. 2. Issuing procedure: p is the transfusion fraction; λ is the crossmatch-recycle time.

exercise of operational control. Some of the areas have been analyzed extensively while others are just now beginning to receive attention from the standpoint of both theoretical and practical considerations.

Issuing Policy

A variation of standard crossmatching techniques can be applied to make most efficient use of the available inventory. Some techniques are the double crossmatch, partial crossmatch or no crossmatch with "type and screen."[2,12] Further, a second issuing control mechanism is the alteration of the recycling time, that is, to change the length of time that a crossmatched unit is held for a given patient.[4]

Operational Control

The blood bank director can make determinations of the amount of blood needed based on the number of patients requiring blood, the average amounts required and their range.[2] The number of patients needing blood reflects the nature of the patient population while the average amounts required reflect the way physicians use transfusions as a therapeutic modality.

Demand Forecasting

The director can apply forecasting techniques to predict changes in the demand both in seasonal variations over relatively short periods of time and trends over longer periods. The director can also exercise operational control in the area of supply procurement. He can determine whether to seek additional blood supply from a supplemental supplier (a central blood bank) or whether to use the local donor pool and how to schedule donors to meet regular or varying needs.

Processing Control

The director has to make a determination as to how much of fresh blood is to be processed into components and how much to be kept as whole blood, how much of the blood brought in from supplemental suppliers must be converted into red blood cells and plasma.

Blood moves from the unassigned to assigned inventory in response to a demand through the process of crossmatching (Fig. 2). Blood is held in the assigned inventory until such time as it is transfused or returned to the unassigned inventory. As a result of many factors, physicians tend to order blood (in a largely predictable fashion) in excess of the amount which is transfused. Therefore, the assigned inventory can be considered to consist of two parts; that which is transfused and that which is held for some period before being returned to the unassigned inventory. That proportion of the blood which is ultimately transfused is called the transfusion fraction, p. That proportion which is not transfused but held for a patient is equal to $1 - p$. After some period of time, λ (referred to as the crossmatch reserve time), this blood is returned to the unassigned inventory. Both p and λ have been shown to have a high degree of variability and contribute significantly to outdating. The transfusion fraction (p) has been shown to vary from 0.25 to 0.67.[3,10,14] While λ is generally two days, it has been shown to go as high as five or even nine days. The profound effects of wide variations in either p or γ may require changes in issuing policy. The most widely accepted and recommended policy called first in, first out, (FIFO) is to release the oldest blood first, as opposed to last in, first out (LIFO) releasing the freshest blood first. It has been shown that when p is low or λ is high, a LIFO policy is preferable to FIFO in terms of limiting the resultant outdating.[4] These variations suggest that a director can exercise better control if he is aware of not only the daily number of units transfused but also of the nature of the patients for whom blood is ordered and the variation in the utilization patterns of the ordering physicians. By altering the issuing policy he can accommodate these variations while minimizing their unfavorable impact.

Analysis has demonstrated that the number of requisitions arriving per day and the number of units requested per requisition are random.[15] The average daily number of units of each blood type transfused, T, is given by:

$$T = (\delta_r \cdot \delta_u \cdot p)$$

where δ_r is mean number of requisitions per day and δ_u is the mean number of units per requisition and p is the transfusion fraction. It is important to note that δ_r reflects the nature of the patient population and therapeutic procedures applied while δ_u reflects the blood utilization patterns of the physicians and may vary widely with the nature of the medical or surgical treatment involved. For a hospital with little surgery, p may be very high. Whereas, for a surgically oriented hospital, p will be around 0.5 and as low as 0.25 or 0.1 for some surgical services within the hospital.

The decision making function permitting an optimal requirements computation for each blood type is given by the formula:

$$S^* = 6.03\ (\delta_r \cdot \delta_u)^{.76} \cdot p^{.12} \cdot \lambda^{-.07}$$

This was derived by the analysis of the impact on system performance of several variables which included parameters of the demand process, the age of supply, the transfusion fraction, the unit cost of shortage, the unit cost of outdating, the crossmatch recycle period, and various issuing policies. The optimal inventory level (S^*) for a small hospital blood bank or for rare types of blood is equivalent to seven to eight times the daily amount transfused modulated by the factor p and λ. For large hospital blood banks or common blood types, S^* is five to six times the daily amount transfused modulated by p and λ. The value of S^* can be more realistically varied if both δ_r and δ_u are computed by forecasting equations which can vary from a simple moving average to more complicated equations such as exponential smoothing which will provide for cyclic fluctuations and long-term trends. Using the equations discussed above, the hospital blood bank director can manage more effectively and operate with a greater degree of efficiency than a random or perhaps intuitive approach may provide. Further, the analysis of issuing policies may illuminate areas where further efficiencies can be obtained. For example, with staff education, p may be increased or λ may be reduced. In addition, use of these equations permits the director to achieve the optimal level of inventory which, while it may not eliminate shortages or outdating, will permit the operation to proceed with the best trade-off between shortages and outdating. Over a wide range of system environments, it has been demonstrated that it is possible to achieve shortage rates of less than 1 per cent for outdate rates between 0.17 to 7 per cent.[5]

Central Blood Bank

There has been a recognition that benefits can be derived by pooling resources in the formation of a community central blood bank. The most apparent benefit is that the hospital blood bank staff is relieved of the responsibility of donor recruitment, blood procurement and processing. This permits the transfusion service to channel its energies and efforts toward the resolution of patient related transfusion problems. Another advantage is the opportunity to pool its widely fluctuating, largely unpredictable demands with those of other hospitals in the system. Within the system the variations cancel each other and produce a smoother, more predictable aggregate demand. This will enable member blood banks to maintain lower inventories without degrading their outdate and shortage performance.

Since the demand to which the central blood bank must respond is generated outside its control, its decision making processes must primarily focus around inventory management. While management decisions regarding donor recruitment, phlebotomy and processing are essential; they can only be handled effectively after efficient optimal inventory control policies have been implemented.

Various areas of blood handling require careful managerial decisions. Inventory control at the central blood bank must set inventory levels to maintain the optimal trade-off between excess inventory with consequent outdating and excessive numbers of shortages. Inventory levels at hospital blood banks and transfusion locations must be suggested or set at a level which will minimize the need for emergency shipments from the central blood bank while minimizing the amount of outdating or return of blood of excessive age. Issuing procedures to govern the distribution of blood from the central blood bank to the various transfusion locations and decision policies governing the transshipment of blood from one transfusion location to another must be developed and modified. Recycle control within the system as well as within a hospital must be exercised with monitoring of the recycle time. Policies must be set regarding the return of aging blood to the central blood bank for reallocation to transfusion locations where the probability of transfusion is high. Following from this is a management decision problem relating to the routing, the frequency, and the volume of deliveries to the transfusion locations.

Managerial decisions relating to component production levels are gaining ever-increasing importance as blood transfusion therapy increases both in complexity and quantity. These decisions involve the determination of both the levels and site (in-house or in the field) of routine component preparation. Another factor is the use of blood component separation devices which permit the preparation of large quantities of components such as granulocytes, platelets and plasma, but require a higher level of technology.

Inventory levels can be set at both the central and member banks by using an outdating/shortage cost-minimizing procedure similar to that which was described for the single hospital blood bank. The optimal inventory level for the central blood bank for each blood type, is a complex function of the number of transfusion locations, the mean daily demand, and the transfusion fraction for all locations served by the central blood bank. Associated with the optimal inventory function for the central blood bank is an optimal inventory level for each member hospital blood bank which is a function of the demand and transfusion fraction for that location.[5]

The relationship between the level of demand and the optimal inventory level (in terms of days of blood usage) for both an independent bank and a member of a central system is illustrated in Figure 3. These figures were computed for an example where the transfusion fraction at each bank, p, is .5 and λ, the crossmatch reserve time, is two days. The level of optimum inventory at a transfusion location can be reduced by 5 to 12 per cent if the location is a member of a central bank. These results have been verified for a wide range of environmental factors.[11]

One of the advantages of a centralized system derives from a carefully determined transshipment policy. Transshipment is the movement of blood from one transfusion location to another at the direction of the central blood bank and implies that the unassigned inventory at the hospitals can be considered as part of the central inventory. By applying such a transshipment policy, the central blood bank can anticipate the outdating or shortage at its member banks and move blood to prevent either or both. A further advantage is gained from the ease with which a central blood bank can initiate an emergency shipment. These permit the hospital blood bank to maintain an optimal inventory level lower than would be required if the hospital blood bank were independent of the central blood bank and unable to avail itself of these benefits.

The cost of outdating includes all of the costs associated with the procurement of the donor, the phlebotomy, processing, record keeping and storage, all of which are not recovered when a unit of blood exceeds its usable life. The cost of shortage cannot include the cost of unfulfilled need for transfusion since this cost is largely imponderable. The costs that are included are those associated with either initiating an emergency shipment from the central blood bank with its attendant increased transport and record keeping costs or initiating a transshipment from another hospital blood bank or transfusion location. If these alternatives are not available or usable, then the cost of shortage includes the cost of locating a donor and the emergency phlebotomy and processing associated with meeting the transfusion requirement or the costs of contacting, fees and shipping from another supplemental source.

The transshipment cost is a minimum for a hospital on a regular delivery route which has a policy of returning blood to the central bank or transshipping once it exceeds a certain age. Emergency transshipment cost is higher. In general, transportation costs are but a small fraction of the cost of outdating or shortages. Therefore, if the probability of shortage or outdate is reasonably high, then a benefit will derive from transshipment.

The transshipment policy states that a unit should be shipped from hospital blood bank i to hospital blood bank j, when the probability of the unit outdating at blood bank j minus the probability of outdating at blood bank i is greater or equal to some number which is the ratio of the transportation cost to the cost of outdating. The transshipment rule for shortage is a similar inequality. Obviously, the left side of the inequality can range between minus one and plus one, but the right side of the inequality is a number that can range from greater than zero to infinity. For practical purposes, the inequality is concerned only with values between zero and plus one. It is also obvious that for areas of moderate size and number of member hospitals, the transportation is only a small fraction of the cost of outdating or shortage. It has been shown that transshipment does not increase significantly while the ratio is below 0.2, that is when the transportation cost is less than 20 per cent of the cost of outdating or shortage.[15] When

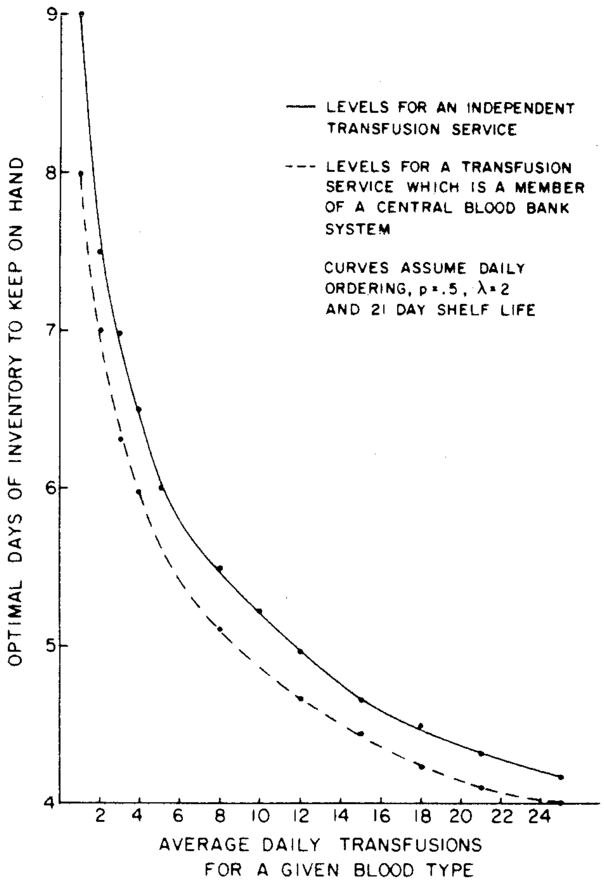

FIG. 3. Optimal days of inventory to keep on hand to meet transfusions for a given blood type.

the ratio is above 0.2, the transshipments increase. A ratio approaching one, indicating a cost of transportation approaching the cost of outdating as it might occur in very large geographical areas appears to be a strong argument for the establishment of satellite facilities and to move from a two echelon system to one with three—a regional system.

It is clear that hospital blood banks which share the services of a central blood bank have distinct advantages over the independent hospital blood banks. These benefits can be grouped under the general term "economies of scale" and are generally effected through the phenomenon of aggregation which works to reduce the variance in random demands by pooling the individual variations into a large single aggregate demand. This permits the local hospital blood bank to operate with an inventory that represents a smaller excess over its transfusion needs. Additional economies of scale are in the area of direct cost of operation which reflect themselves as lower charges, *i.e.*, as the volume of activity rises, the cost per unit decreases. An additional benefit of such resources sharing is the ability to further minimize both shortages and outdating by transshipment.

Regional Blood Bank

For the purposes of this discussion, a regional blood bank is the third echelon of the regional structure. The hospital blood banks or transfusion locations are the first level, two or more central blood banks are at second level and the regional blood bank is at the third level. It is possible to view the regional blood bank in two ways: in one view, the regional blood bank is a single central blood bank which also has satellite facilities whose responsibilities are limited to such functions as phlebotomy and processing for a small geographic area. Donor recruitment and delivery for the entire region is controlled from a central office in the regional blood bank.

In the second form, no "wet" blood banking takes place. Under these conditions, the regional blood bank has the strictly administrative function of directing centralized donor recruitment and donor procurement and the administration of the network of central blood banks with responsibilities for allocation of activities. In addition, this regional blood center would be responsible for such things as interaction with the various government agencies, the maintenance of the license for operation of the blood banks within the regional area, equipment maintenance, legal advice, quality control and long range planning.

Mathematical modeling techniques have just begun to be applied to the problems pertinent to the concepts of regionalization. Because the geographic area conceived as the domain of a regional blood center is far greater than the area generally considered for a central blood bank or community blood center, the main thrust of the analysis from an operations research standpoint has been in the area of transportation problems. A second consideration at an early stage in the evolution of relevant modeling techniques is the consideration of the upper bound on the economies of scale. As alluded to before, the majority of mathematical models used encompass convex functions, that is, the zone of optimality is bracketed by zones of diseconomy or suboptimization. so that as one moves in either direction away from the optimal zone, one encounters increasing cost or suboptimal conditions of operation (Fig. 1).

From these considerations, it is apparent that once a blood banking system is operating in the zone of optimality, to expand to include more geography and/or greater volume of activity may produce diseconomies which can only be counteracted by subdivision of the broader region into smaller areas by the use of satellite facilities. A planning model was designed to address the problem of a regional system.[9] It includes in-puts in the following areas: 1) the actual geographic location of the central blood banks in the system; 2) location of all the hospital blood banks in the system; 3) optimal inventory level determinations at the various hospitals in the central blood banks serving them; 4) the demand and transfusion characteristics p, δ_r, δ_p; 5) the transportation costs for routine and emergency shipments, and 6) the shortage and outdate cost functions already described. By using the locations, capabilities and volumes of activity of already existing central blood banks, allocation of the hospital blood banks can be made to each of them in such a way as to minimize all of the cost factors concerned. This will generate one or more networks, each of which represents the optimum configuration of users. For example, Figures 4 and 5 show the plot of allocation loops for the hospitals in the Chicago area assuming the location of three and four hypothetical community blood banks respectively.

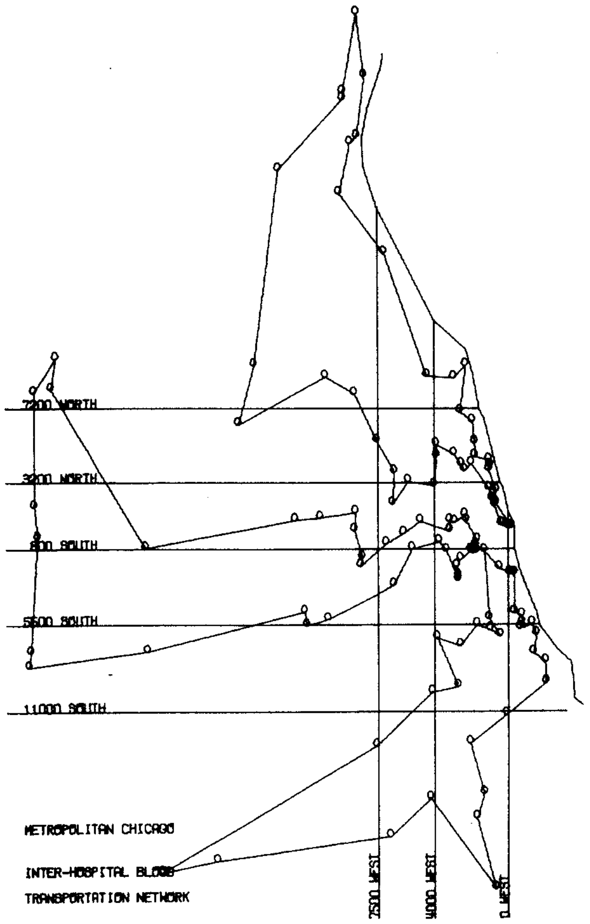

FIG. 4. Computer plot of locations of hospitals in the Chicago area and their allocation to transportation loops assuming three central blood banks.

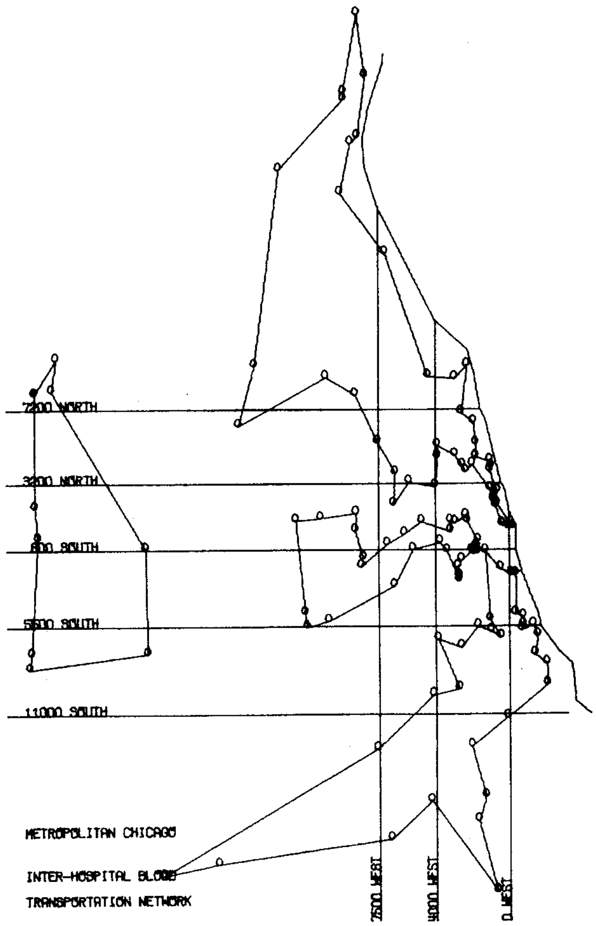

FIG. 5. Computer plot of locations of hospitals in the Chicago area and their allocation to transportation loops assuming four central blood banks.

The alternative method is to analyze all of the existing hospital blood banks and transfusion services, their levels of activity, their distances from each other, transportation problems unique to any one or several of them and determine the minimum number and the location of central blood banks which would serve them in an optimal fashion. This technique implies the disassembling, at least in part, of the existing structure to achieve regionalization. Response to the mandate of the American Blood Comission to build on the present system and the realities of blood banking make it most feasible to accomplish any change by a step-wise adaptation of the existing system using information gained from the application of the model's first alternative and its more sophisticated modifications currently being developed.

Summary

Use of modeling techniques permits the development of a mathematical response function which expresses the quantitative aspect of performance measure for a critical activity in terms of several other variables. From this response function, an optimal level for that activity can be determined. This optimal level will represent the best trade-off between the factors selected as important such as outdating and shortages. The use of these functions can be expanded to permit decision-making in several critical areas which will serve to make maximum use of the available inventory at minimum overall cost. The basic equations can be adapted to the second echelon of activity in a regional blood banking system and provide decision-making policies for central community blood banks with the benefits derived from the economies of scale extending to the member hospital blood banks. Finally, the third echelon of blood banking activity at the regional level, the analysis of which is still in its early stage, combines the transportation problems associated with large geographic areas with the cost-optimizing functions described for hospital blood banks to arrive at a model which can be analyzed and serve as the basis to build a sound structure for a regional blood banking system.

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M. A. Cohen, Department of Decision Sciences, The Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania 19104.

W. P. Pierskalla, Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, Illinois 60201.

R. J. Sassetti, Rush-Presbyterian-St. Luke's Medical Center, Chicago, Illinois 60612.

J. Consolo, Chicago Regional Blood Program, Chicago, Illinois 60614.