OPERATIONS RESEARCH AND SYSTEMS ANALYSIS

Hugh J. Miser

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Foreword

During 1980 <u>Science</u>, the weekly journal of the American Association
for the Advancement of Science, will celebrate its centennial by publishing
a Centennial Issue containing, in addition to five articles on the history
of science, articles on the current state and future prospects in astronomy,
the behavioral and social sciences, biology, chemistry, the earth and
planetary sciences, mathematics, physics, medicine, engineering, industrial
research, operations research and systems analysis, world population, food
and nutrition, energy, environment, rural development, communications, and
science and technology in the developing countries.

Following an invitation from Philip H. Abelson, Editor, I prepared the
draft of an article on operations research and systems analysis, which was
circulated to some 30 leaders in these fields in the United States and at
IIASA. The present version took account of many of the comments and sug-
gestions that these persons were kind enough to forward to me.

My instructions were primarily to emphasize key recent developments
as they may affect the future; however, since this is the first such piece
to appear in a journal of so wide and varied a readership, I adopted the
additional goal of introducing the general reader with some scientific
interests to the subject and of showing him how it grew out of the older
sciences, and how it is a natural expression of scientific growth in our
time.

Since space was severely limited, this complex of goals made it
necessary to leave almost everything of interest to the OR/SA professional
out, particularly since I felt that some well chosen examples would say
more to the intended audience than a series of generalities. This fact
made the choice of what to include difficult. No doubt another author
would have chosen differently, as the comments from my many professional
colleagues indicated. However, choices had to be made within space limi-
tations, and they were made on the basis of what seemed most important to
me and what would fit into a reasonably brief discussion.

In preparing this paper I had two hopes: that it would be an inter-
esting and useful introduction to many persons who may have wondered what
operations research and systems analysis are, and that it would suggest
some useful points of view to practicing analysts in these fields.

February 18, 1980   Hugh J. Miser

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Summary

The science of man/machine operating systems, which includes operations research and systems analysis, has achieved a substantial body of theory and application over the last forty years. Its current strength prompts it to attack difficult large-scale problems, in spite of their manifest difficulties, while challenging the other relevant sciences to unite, not only with each other and operations and systems research, but also with society, to deal with some of the most widespread and important problems of our time.

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Operations research, unlike most sciences, is able to point to a well defined combination of circumstances and events that not only began its activities as a coherent development but also caused its name to be coined. After Hitler rose to power in Germany, England sought to prepare a suitable defense against possible air attack, with the result that, by late 1937, the key elements of an effective defense had been devised: radar and the Hurricane fighter plane. But combining them into an effective system could not be left to improvisation, as the disappointing results of an air exercise showed in July 1938. Consequently, A. P. Rowe, then leader of the radar development work on England's east coast, proposed that research into the operational—as opposed to the purely technical—aspects of the radar/fighter system be undertaken, and the term "operational research" was coined to describe the work (1).

This new kind of research, conducted in close cooperation with the officers and men of the Royal Air Force, led directly to substantial improvements in England's air defense system, which was given its most decisive test in the Battle of Britain during August and September of 1940.

The success of this partnership between scientists and operating forces prompted the spread of operational research to other British commands and services. When the United States entered the war, this British precedent was pursued by US military commanders, with the result that, by late 1942, groups of scientists were undertaking similar work for both the US Navy and Army Air Corps. However, the name had been Americanized to "operations research."

By the end of the war, England, Canada, and the United States had employed perhaps as many as 700 scientists in work loosely described by these terms (2).

Some of the work that these scientists did merely exploited the technical backgrounds that they brought to their wartime tasks. However, there was

also the important novelty that they had studied and evaluated the results

of tactical operations, devised tactical innovations and predicted their

possible consequences, and, when the innovations were actually used, com-

pared expected results with those actually achieved. And this knowledge

had often become the basis for helping with tactical planning, and even,

during the later stages of the war, for contributing important knowledge

to strategic choices.

History shows that operations research workers made important contri-

butions to the war efforts of their countries. However, another outcome of

this work was also important: Many of these scientists saw in their wartime

scientific achievements the germ of a new science of operating man/machine

systems that could be developed for peacetime activities and applied to

their problems.

The Science of Operations Research

It is clear that many of these pioneers of operations research saw

their work as being scientific; for example, as early as 1941 P. M. S.

Blackett (a physicist who later won a Nobel prize for his work on cosmic

rays), in a memorandum on "Scientists at the Operational Level," emphasized

that the work was "scientific analysis of operations" and should be staffed

and carried out in the spirit of science (3). This memorandum had consid-

erable influence on both sides of the Atlantic.

Many of the scientists who became involved with this wartime work were

surprised to find that there were identifiable stabilities in situations that

they had always considered to be totally formless. For example, consider

the outcomes of air combat. While a commander can control his own tactics,

he cannot control those of his enemy, and the surrounding weather conditions

also introduce an element of uncertainty. Nevertheless, it was often possible

to predict the outcomes with considerable accuracy (4).

The sense of wonder that such systems of men and machines operating

in conflict in a natural environment could exhibit aspects of regularity was expressed by two of the most notable US operations research pioneers, Philip M. Morse (a physicist from Massachusetts Institute of Technology) and George E. Kimball (a chemist from Columbia University), when they wrote in 1946 that "large bodies of men and equipment carrying out complex operations behave in an astonishingly regular manner, so that one can predict the outcome of such operations to a degree not foreseen by most natural scientists" (5).

Too, the World War II experiences had exhibited the classic cycle of the method of science (6): The scientists had observed nature (albeit the startlingly new phenomena of military operations), had built theories to account for these observations, had used them to predict future outcomes, and had tested these predictions against actual experience, with frequent agreement. Indeed, many of them had experienced several connected and successive cycles, from which had emerged fairly comprehensive theories with accepted predictive value. Thus, the novelty of wartime operations research did not lie in the method that was being used, but rather in the part of "nature" to which it was applied: military operations.

The consequence was a natural one: Many scientists emerging from this experience expected that it could be extended to a wide variety of civilian peacetime operating systems.

By the end of the first decade after the war, examples had begun to emerge to give substance to this expectation (7), and by now their number and variety are very great (8).

In 1979 Eric Brodheim of The New York Blood Center and Gregory P. Prastacos of the University of Pennsylvania reported a notable study of blood distribution and utilization that exhibits key aspects of such work (9). The national problem they were responding to is this:

> Each year over two million hospitalized Americans depend
> upon the timely availability of the right type of blood products

at 6,000 hospital blood banks (HBBs) in the United States. If the
right blood products are not available at the HBB when required,
then medical complications or postponements of elective surgery
can result, which translate to extra days of hospitalization and
expense. On the other hand, since most blood products may only be
administered to a patient of the same blood type within 21 days of
collection, overstocking at HBBs leads to low utilization, which
increases costs and is wasteful of the scarce blood resource.

Or, as Johanna Pindyck, Director of the Greater New York Blood Program (the
largest in the world), puts it, "We face the major problem of how to maxi-
mize the availability of blood to each of . . . 262 hospitals . . . while
effectively discharging our implicit covenant to our donors to see that
their gift is efficiently utilized."

Since there are approximately 200 Regional Blood Centers (RBCs) in the
United States, Brodheim and Prastacos viewed the problem from the RBC point
of view, as well as from that of the HBB:

Most blood products in the United States are derived from whole
blood that is collected by an RBC in units of one pint from volunteer
donors. After laboratory processing and testing, whole blood and blood
products derived from whole blood are distributed to the HBBs, where
they are stored to be available for transfusion when requested.

The complexity of the blood inventory-management problem is due
primarily to the perishability of blood, the uncertainties involved
in its availability to the RBC, and the fluctuating demands and usages
at the HBBs. Too, there are large variations in the sizes of the HBBs
to be supplied, in the relative occurrence of the different blood
groups, and in the mix of whole blood and blood products used at each
HBB. Finally, the performance of a regional (or hospital) blood-
management system can be evaluated in terms of multiple criteria

(or objectives), some of which conflict (e.g., availability vs. utilization of blood at an HBB), or involve costs that are difficult to estimate (e.g., the cost of unavailability).

As a result of this complexity, regional blood management systems have historically been decentralized and reactive in nature, characterized by the HBBs placing daily orders to bring their inventory to what each considered a safe value, and the RBC trying to fill these orders, as they came, while keeping a necessary buffer in the stock. This created a feeling of uncertainty, as a result of which HBBs have generally tried to maintain high inventories of most of the 8 different types of each of these products in order to provide high availability to satisfy patient needs, and have accepted the low utilization resulting from spoilage. Consequently, the national utilization rate of whole blood and red blood cells prior to expiration was estimated to be only 80 percent in 1974.

After becoming thoroughly familiar with the practical operations of the Long Island blood distribution system, which was the test bed for their analysis, Brodheim and Prastacos reasoned that three important management concepts should be introduced into the approach that they were exploring:

Instead of individual ordering from every HBB, a regional management system has to be developed that will allocate most of the available regional resources among the HBBs so that they are utilized most efficiently. This calls for some form of centralized decision making at the RBC, which will operate under objectives of overall regional efficiency, as opposed to the existing mode of decentralized decision making, operating under objectives of local (i.e., HBB) efficiency.

Any regional strategy that allocates blood products to be retained until transfused or outdated will result in low utilization,

especially in the case of the small-usage HBBs which, in aggregate,
account for the largest part of overall blood usage. Consequently,
some form of blood "rotation" is required whereby freshly processed
blood is sent to an HBB, from which it may be returned, some time
later, for redistribution according to the regional strategy.

It is also desirable that a significant portion of the periodic
deliveries to the HBBs be prescheduled. This way the uncertainty of
supply faced by the HBBs is reduced, with a resulting improvement in
the planning of operations, and the utilization of their resources.

While a brief sketch can only suggest the depth and subtlety of the analysis,
it is nonetheless helpful in understanding the nature of the results.

The blood needs of an HBB can be expressed as the demand (that is, the
number of units required to be on hand for possible transfusion) and the usage,
(that is, the number of units actually transfused). On the other hand, from the
RBC point of view, the effectiveness of the supply management can be measured in
terms of two rates: the availability rate (that is, the fraction of days when
the inventory of a given blood type on hand is sufficient to meet the demand),
and the utilization rate (that is, the fraction of the supply that is trans-
fused). The first task of the analysts was therefore to devise a model that
translates demand and usage to availability and utilization rates as functions
of RBC blood-distribution policies and HBB blood-stocking policies.

Since the availability rate at an HBB depends only on the pattern of
demand and the inventory level, it could be explored on the basis of blood-
bank data. The analysts found sufficient stability in the evidence to
establish the "universal" piecewise linear relation between inventory level
and mean daily demand, with the availability rate as a parameter, shown in
Figure 1. Tests showed that the ability of this model to predict was high.
The availability rates that HBB managers considered to be adequate ranged
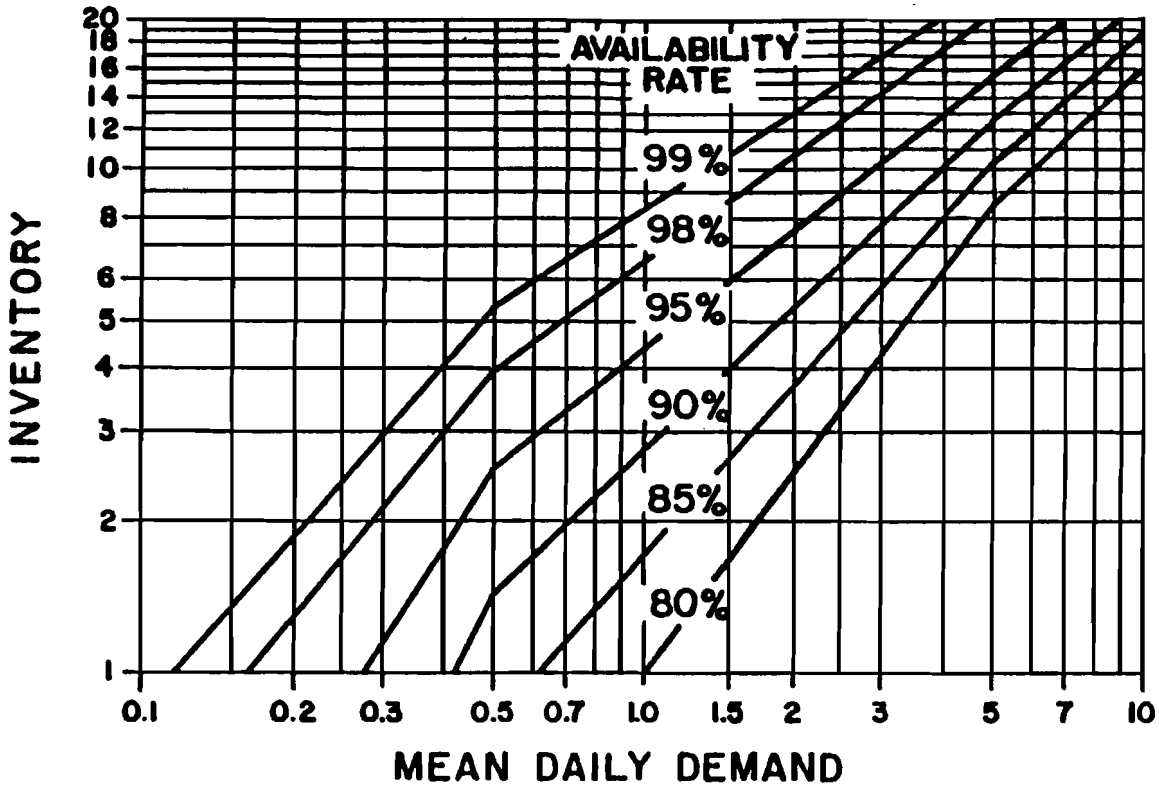usually from 85 to 95 percent.

Figure 1. Inventory levels and mean daily demands for blood units for given availability rates at hospital blood banks.

The utilization rate depends on the size and age mix of the blood supply in an HBB, as well as the demand. The distribution strategy is also an important issue. After consultations with the HBBs, and in agreement with the management concepts outlined above, the following class of policies was chosen for analysis. Each HBB receives periodic shipments at intervals between 1 and 4 days long (to be determined from the analysis, depending on the size of the HBB, and other considerations). Each periodic shipment to the HBB includes a number of fresh (or, long-dated: 1-2 day old) rotation units and a number of older (or, stock-dated: 6-7 day old) retention units. The latter are retained until transfused or discarded, but the rotation units that are in excess of a fixed desired inventory level at the end of the period are returned to the RBC for redistribution. Modeling this situation called for a finite-state Markov chain analysis.

Having derived these models to predict the HBB availability and utilization rates for any policy implemented by the RBC, the analysts examined the regional allocation problem, assuming that there were fixed penalty costs associated with nonavailable and nonutilized units. They found that the policy minimizing the total expected one-period cost was:

(1) first allocate all available retention units so as to equalize the utilization rates at all HBBs;

(2) then allocate all available rotation units (which are not subject to spoilage (while at the HBB) so as to equalize the availability rates at all HBBs.

It was also shown that this policy is independent of unit penalty costs, and that it maximizes both the availability and utilization of blood in the region simultaneously. That is, any deviation from the policy that would reduce utilization would also result in reduced availability for the next period, and vice versa.

In addition, the analysts found that the short-term policy had the same structural characteristics as the policy which was optimal over the long run, and even that the utilization and availability rates calculated for the short term corresponded very closely to the optimal values for the long run. Thus, they could return to the result showing that the distribution policy listed above for the one-period case was optimal and establish the principle that:

A distribution policy should seek to equalize utilization rates and availability rates among the HBBs in the region. This is also a policy that has the essential elements of "fairness" in spreading equally the nonavailability and nonutilization risks amongst hospitals regardless of their relative size, and is consequently a highly defensible policy.
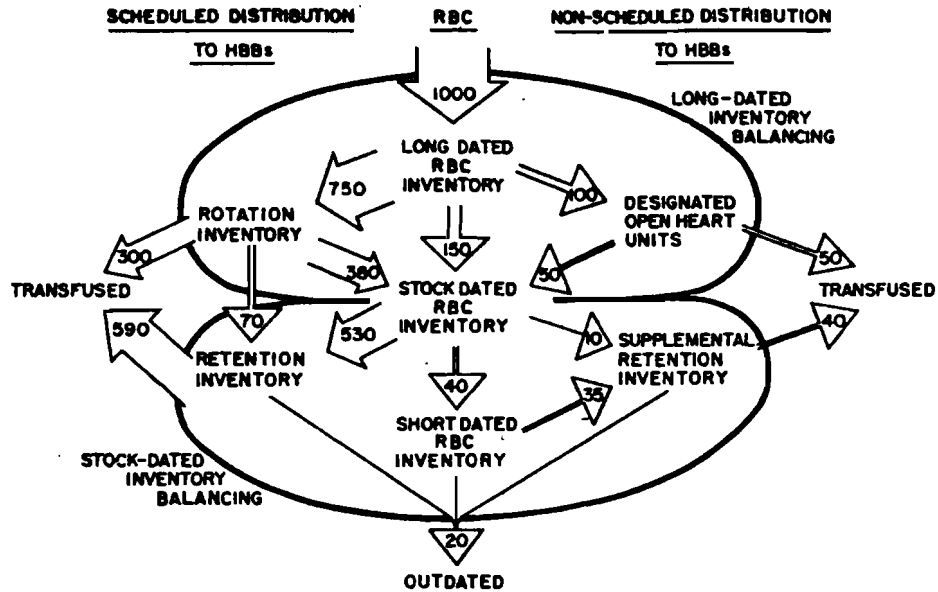
Figure 2. Illustration of a planned regional blood flow.

With these results in hand, the analysts formulated the problem as a mathematical program, which they used to determine the appropriate distribution policy for the region (Figure 2 gives an example of such a policy).

They then turned to the task of implementation in their test region, the Long Island blood distribution system. This is an important story in its own right, but too long to summarize here. It was carried out in a sequence of planned steps, and was characterized by continuous interaction with the medical and administrative personnel, design of the necessary forms and procedures, educational sessions with the users, and development of an automated computer-based information system. The results have been gratifying: utilization and availability have improved significantly, wastage has gone down by 80 percent, and delivery costs reduced by 64 percent.

The administrative system derived from these results (10), which has been in operation on Long Island for three years, is being extended to the rest of the Greater New York Blood Program, and is being considered for introduction elsewhere in the United States and abroad.

This example exhibits the pattern familiar to the wartime operations research analysts, and one that remains central to successful operations

research work to this day: problem, observation, theory building (usually called modeling today), problem solution based on calculations from the theory, devising a system to be implemented, and testing it in actual practice, the analysts keeping in close touch throughout with the situation being studied and with the persons involved with it. To which should be added two aspects that this brief example did not treat: implementation brings new problems for analysis, and a changing underlying situation may call for revisions in the basic research.

The Methods

Almost all of the work during the war borrowed methods and theories from existing fields--mathematical analysis, probability, statistics, and the natural sciences--with only an occasional new model being assembled from these elements to represent the new aspects of nature that the analysts were exploring. The most notable exception was a theory of search developed as part of the work for the US Navy (11).

The early post-war work followed the same pattern. Thus, it was hardly surprising that Philip M. Morse, in retiring from the office of the first President of the Operations Research Society of America in 1953, said that "one of our major tasks . . . is to develop analytic techniques and to broaden their range of application" (12), a feeling that was widely shared at the time.

The operations research community's response to this challenge was remark-able for its depth, comprehensiveness, and fecundity. The flow of theoretical developments quickly became a flood that continues unabated to this day. Thus, in modest space one can only mention important currents, relying on the reader to consult the excellent new Handbook of Operations Research (13) for further elucidation and guides to important literature. The result is that today's operations research worker has a wide and varied spectrum of models to work with.

Some theories that already existed were extended significantly: the theory of stochastic processes represented many systems of interest to

operations research workers, who contributed to its development; the related theory of queues, entering a mature period in 1950 owing to its extensive application in telephony, developed explosively, not only because of its mathematical challenge, but also because of the widespread occurrence of queues in the life of modern society and therefore in the systems studied by operations research workers; optimal control theory advanced in response to operations research problems; value theory, since it deals with the key issue for operations research of what importance to attach to various possibilities, was pushed forward vigorously; and game theory, which offered a challenging framework for thought about operational problems and choices, was pursued energetically.

However, operations research has also produced new theories offering not only significant intellectual challenge but also important vistas of potential application. The best known of these is, of course, linear programming, which, like queuing theory, has developed explosively in the three decades since the 1947 development of the simplex method by George B. Dantzig (who received the US National Medal of Science in 1975 for his work in this field); the important related fields of integer programming, geometric programming, nonlinear programming, large-scale programming, and stochastic programming have also been developed to considerable depth under the pressure of need in applications. Owing to the important place that the concept of decision assumed early in the history of operations research, a theory of decision has emerged to deal with the attendant difficulties, particularly those arising when multiple and competing criteria are present; dynamic programming has been developed to deal with many kinds of sequential decision problems; the theory of flows in networks contains a mature body of knowledge that has undergirded a wide variety of applications; the theory of simulation has played an important role for problems where analytic theories are cumbersome or inaccessible, but where practical imperatives push the analyst to results; and the art of heuristic problem solving is

playing a growing role in handling problems of high computational complexity (13a).

Arenas of Application

As operations research workers, armed with their methods (some old, but also many new ones—including those just mentioned), have dealt with the operations and problems of business, industry, and government, they have observed many conceptual strands common to various operational processes. Thus, they have assembled groups of methods and models appropriate to common functional processes such as these: production planning, inventory control, facilities location and layout, scheduling and sequencing, project planning and control, reliability, maintenance and replacement, marketing, human resource management, and forecasting (14).

These common functional processes occur in many arenas of application and methods and models can thus be widely applied. However, such arenas also offer difficulties of their own for which analyses can inform decisions about operations, policies, or plans. The Handbook of Operations Research devotes chapters (15) to eight such arenas (urban services, health services, educational processes, transportation systems, military systems, electric utilities, the process industries, and the leisure industries), but the list can easily be lengthened to include banking, advertising, university administration, state and local government, federal government, highway safety, communication-system management, agriculture, library and information-system management, mining and the mineral industries, forestry and forest products, and many more (16).

The concerns of business and industry—and of management generally—bulk large in these lists, which accounts for why much of the work is carried out and reported under the rubric of "management science." However, only a stickler for fine detail would trouble to distinguish management science from operations research by more than the practical context of the work (17).

Lest the preceding discussion suggest that operations research can flourish only in big institutional contexts, let us turn to an issue of local governmental concern: a school-desegregation issue in a community of modest size.

In 1954 the Supreme Court of the United States ruled that segregated schools for black and white children were an unacceptable form of public education and that schools should begin admitting students to schools without racial discrimination "with all deliberate speed." A 1968 decision had the effect of speeding up the process of desegregation, and, to this end, it gave federal courts the authority to order busing school children as one way of achieving the desired goal.

Any casual newspaper reader is aware of the storm of social and ethical issues that arose from these landmark decisions. However, he may be unaware that, at the root of the matter, there were two very practical difficulties facing school boards and school officials:

● What precisely, in quantitative terms, does the court mean by deseg-regation? Must every school have the same distribution by races as the regional population? Or is there some maximum allowable variation? The decisions did not deal directly with these questions, so the only course open to a school jurisdiction was to devise a plan, calculate the resulting school population distribution, and then submit it to the court to see whether or not it would win approval.

● In devising and implementing such a plan, the practical difficulties of school and bus assignments are formidable, particularly if, as is usually the case, the numbers of schools and students are large, and if some rather practical constraints (such as restricting the amount of additional travel for students) are considered.

When the School Board of Alachua County, Florida (in which Gainesville is located) faced these difficulties, they were able to obtain the assistance

of Peter C. Belford and H. Donald Ratliff of the science faculty at the
University of Florida.

These two investigators approached the first of the two difficulties
in this way, as explained in a 1971 account of their work (18).

> In order to get some feel for what the courts consider to be
> "acceptable" desegregation plans, we contacted a number of organiza-
> tions, including the Department of Health, Education and Welfare and
> the National Association for the Advancement of Colored People,
> requesting any available information concerning desegregation plans
> that had been submitted to the courts for approval. In every case
> these organizations were either unable or unwilling to provide this
> information. We were finally able to obtain from individual school
> districts ten plans that had been accepted by the courts since 1967.
> These plans were from school districts in Alabama, California,
> Florida, and Georgia, and were approved by several courts.

Since the courts did not give reasons for accepting these plans,
an attempt was made to determine empirically from them some quantitative
measures of acceptability upon which future plans could be based. Two
measures that seemed reasonable were the maximum allowable deviation
from the actual percent black in a given district, and the average
allowable deviation from the actual percent black in a given district.
Since a number of the plans had at least one school that was almost
all white or almost all black, the maximum deviation provided little
information.

The available information on the allowable deviation for a given school
from the actual percent black in a given district showed figures as big as
34 percentage points for schools with more blacks than the district average
and 24 points for schools with fewer blacks than the average. However,

it appeared, when the court decisions were viewed over time, that the allow-
able deviations from the district percentage of blacks were decreasing.
Therefore, the School Board of Alachua County, with this trend in mind,
decided arbitrarily to seek a plan that would keep the percent black within
five points on either side of the district percentage of 30 (in other words,
each school would be required to have between 25 and 35 percent blacks), a
decision that would yield an average deviation from 30 percent of somewhat
less than five points, a figure small enough to appear likely to gain court
approval.

With this constraint decided upon, the next step was to consider the
problem of assigning students to schools to meet the desired objective, plus
others that might be appropriate (such as keeping the additional distances
traveled by students down to acceptable levels).

To paraphrase the technical arguments of the analysts, they constructed
a model of the situation in this way: The school district under consideration
was divided into a fairly large number of student locations, each location
being considered to be where the students are who live in the immediately
surrounding area; this location may be thought of as the location of a school-
bus stop. For each location two sets of facts were known: the numbers of
white and black students, and the distances from the location to each available
school in the district. The distance considered was the distance that would
have to be traveled by a vehicle on streets to go from the location to the
school by the most direct route.

The decisions to be made using this starting point are how many white
and how many black students from each location to assign to each school
under these restrictions:

1. Each student is to be assigned to exactly one school.

2. Each school is to have assigned to it a number of students equal
to its capacity, which is known in advance.

3. The proportion of black students assigned to each school must lie

between 25 and 35 percent of its capacity.

In addition, some desirable features were added: No assignment would be made that caused a student to be bused more than ten miles from home to school, and no student who lived within two miles of an appropriate school would be bused at all (that is, the student would walk to his nearest neighborhood school).

Finally, a very important objective was introduced: to make the assignment so as to minimize the total student-miles traveled.

Some transformations of this formulation allowed it to be recognized as a minimum-cost flow problem in a single-commodity network, for which there is not only adequate theory but also several efficient methods of computation.

The analysts used this formulation

. . . to generate a desegregation plan for the school system of Gainesville, Florida. The school district was divided into one-quarter-square-mile blocks. Each block was considered as one student location. The school board had previously compiled the number of black students and the number of white students at each of these locations as well as their current grade assignment . . . The desired number of students in each school and the desired bounds on the number of black and white students in each school were provided by (the superintendent's office) . . . Each school district was designated as either an elementary school (kindergarten through fifth grade), a middle school (sixth through eighth grades), or a high school (ninth through twelfth grades). Each system was then treated independently . . .

For the elementary-school system there were 6887 students (of whom approximately 30 percent were black), 298 student locations, and 11 schools. The computed results for this system were:

● Percent black: 25 (four cases), 29, 33, 34, 35 (four cases).

O assigned to School 1
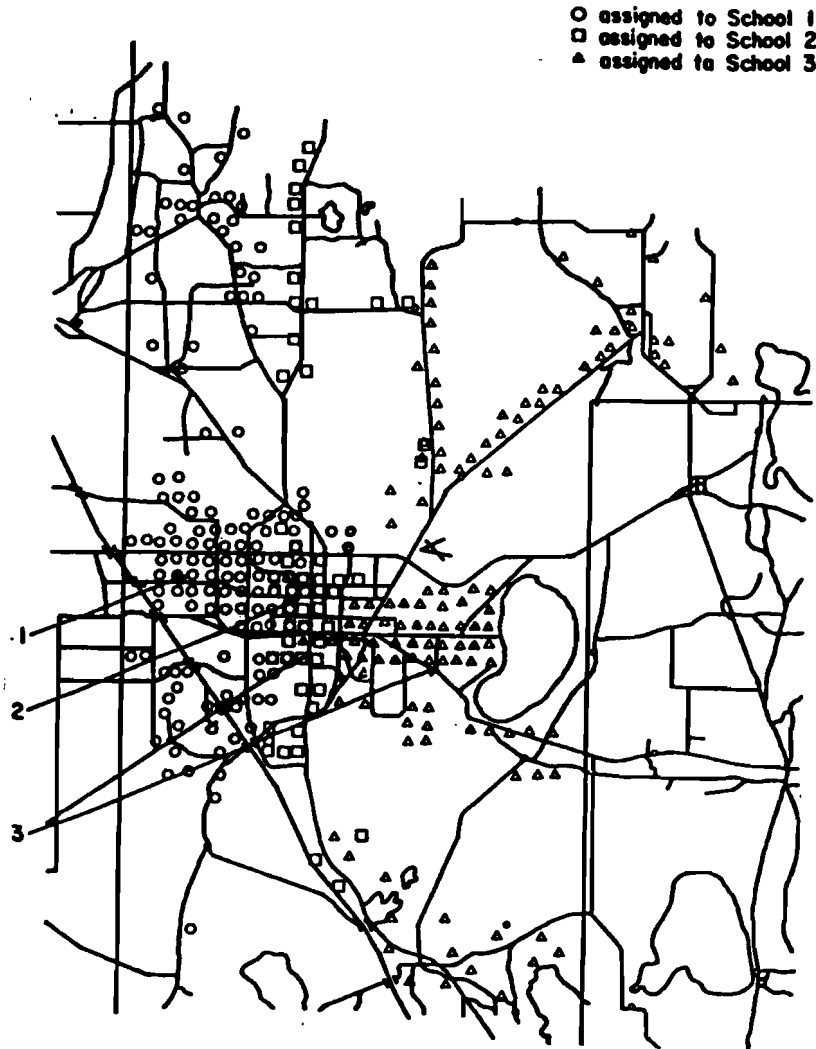□ assigned to School 2
▲ assigned to School 3

Figure 3. Assignment of student locations to schools for the high schools of Gainesville, Florida.

● Average number of miles traveled by the 2005 bused students (of whom 944 were white and 1061 black): 6.

● Total number of student-bus miles: 11,628.

Similar results were obtained for the middle and high schools. Figure 3 shows how the student locations were assigned to the three high schools.

The desegregation plan generated by the model was used as the basis for rezoning the schools in Gainesville; while some minor changes were made by the school officials, the final districts put into operation were almost indistinguishable from those derived by the computer (19).

As quite often happens, this carefully defined and somewhat restricted study shed some light on other issues, notably the concern of the public that busing to achieve integration would involve students in long time-consuming rides. However, a supplementary analysis showed this fear to be largely without substance: A comparison of the desegregation assignment with an optimal assignment of students to schools without regard to race showed that the racially balanced assignment increased the student-bus-miles by only 20, 6, and 7 percent for the elementary, middle, and high schools, respectively. "The results indicate that the actual increase in busing is much less, at least for the Gainesville system, than one might anticipate."

Systems Analysis

Since the brief account of the wartime work in operations research showed how the work began in tactics but grew into planning and strategy, it is natural to look for a similar pattern in postwar work. The two examples we have sketched deal with tactical work, but must not be read to suggest that only tactical work has been done. Rather the wartime pattern has been followed: solid foundations in tactical understanding have led to involvement in planning and strategy in many arenas (notably in defense and large corporations, but with instances of successful involvement in many other contexts as diverse as local government and university management).

However, throughout this experience the analyst has had borne in on him a fact of overriding importance: Each system he has worked on is merely a subsystem in a larger system, indeed, one of an ever-widening congeries of systems. Thus, just as the radar/fighter system was part of a larger warfare system for the defense of England, the regional blood collection and distri- bution system supports the hospitals of its region, which are a part of the nation's health-care system; the school-busing system for Gainesville is a supporting subsystem in the educational system for this city.

Consequently, the purposes of the subsystems are subservient to the purposes of the larger systems of which they are parts. For example, the school-assignment study aimed to use the buses to achieve a rough equality of the proportion of blacks in each school, the equal-proportion objective being an expression of a goal of the social system in which the school system was embedded. Similarly, the objectives the analysts adopted of having the students within two miles of their schools walk there and of limiting any bus ride to less than ten miles are quantitative interpretations of social goals perceived to be held by the community. Finally, it is significant to note that, for the busing system to contribute to the goals of the larger system of which it is a subsystem, it has to operate somewhat "inefficiently," if we interpret efficiency as the subsystem objective of getting the students to school with a minimum of travel.

Thus, the success of operations research workers in developing scientific theories describing important classes of phenomena occurring in man/machine operating systems and in using these models to solve problems arising in these systems has inevitably driven them to study larger and larger systems: in other words, to what has come to be called "systems analysis" (20).

But this imperative arises because it is intrinsic to the problems that society has, and the ways they are embedded in large systems. For example: our highway traffic system combines drivers and passengers, pedestrians, roads, vehicles, the customs and rules of the road, the weather, the surrounding environment, and the energy sources that make it work; our energy system includes the sources from which we derive energy, the means for converting these sources to usable forms, the distribution devices and procedures, the using community (including the highway traffic system), the political and international environment that affects energy deliveries and costs, and the

natural and economic environment in which energy is used (and that is affected by energy use); the analyst concerned with air quality must study a system consisting, not only of the atmosphere and the natural global and terrestrial features that affect its behavior, but also of the patterns of human activity (including both transportation and energy use generally) that contribute to the deterioration of air quality; and so on. The familiar problems of highway safety, energy, and air quality arise in the operations of these systems.

As the operations research analyst is driven toward considering the operations of these larger systems, his classical partnership with the operators of the smaller subsystems (the officers and men of the RAF Fighter Command in the wartime example, the managers of the regional blood centers and the hospital blood banks, the School Board and school administrators of Gainesville) has to be extended to include, not only operating and policy officials with much larger purviews, but also scientists with other specialties relevant to the problems. For example, a comprehensive study of an air-quality issue could demand not only operations research analysts and meteorologists but also demographers, economists, statisticians, chemists, energy-systems engineers, and regional planners—in addition to the appropriate officials who should also participate in the work.

Thus, although historically systems analysis emerged largely from the early operations research work, as it is conducted today it is highly interdisciplinary. However, to reach its highest goals it must be pandisciplinary in the sense of combining the contributions of the various supporting disciplines into new syntheses—in other words, into new science explaining the behavior of the large systems it is studying.

Since major systems analyses are nearly always closely associated with major institutional policy decisions (21), the reports that describe them often do not find their way into the archival literature of science. Complete treatments are always too long for the usual journal article, and

book-length treatment is somewhat deterred by the context of much of the work. Nevertheless, a scattered literature is emerging, both to describe case studies and to provide overviews of how such work is done (22).

From experience in the field as reported in this literature a sort of central paradigm for systems analysis has become widely understood among systems analysts. They expect a reasonably comprehensive systems analysis to:

● Marshal both the evidence relating to the problem and the scientific knowledge bearing on it, when necessary, gathering new evidence and developing new knowledge.

● Examine critically the social purposes—those of both persons and institutions—relating to the problem.

● Explore alternative ways of achieving these purposes, often including designing or inventing new possibilities.

● Reconsider the problem in the light of the knowledge accumulated during the analysis.

● Estimate the impacts of various possible courses of action, taking into consideration both the uncertain future and the organizational structures that must carry these courses of action forward.

● Compare the alternatives by applying a variety of criteria to their consequences.

● Present the results of the study to all concerned in a framework suitable for choice.

● Assist in following through on the actions chosen.

● Evaluate the results of implementing the chosen courses of action.

However, because these steps are listed here in order, it would be a mistake to infer that they take place in this order in a systems-analysis study. Rather, there is almost always a great deal of recycling of ideas and analysis; for example, the impacts of the chosen courses of action may dictate reconsidering the social purposes, the analysis of the chosen alternatives may generate new and more interesting ones for consideration, and so on. Nor do all systems analyses carry out all of the steps; the

user may need only some of the steps carried out. Since the world does not stand still while the work is going on, its changes may dictate major changes in content and approach, or, since user representatives must work with the analysis team throughout if the work is to be effective, early results may get translated into action or policy quickly. All of these influences may change the pattern of the work.

From a professional point of view, what sort of work does the systems analyst do? We can expect him to: observe and describe the behavior of complex systems; build models, where they are needed, to explain these observations, and test the extent of their validity for the purposes of his analysis; use these models, in combination with other knowledge and constructs, to deduce and synthesize descriptions of the behavior of important segments of the systems under study; use technical ingenuity and design synthesis to devise programs or courses of action; devise methods of generating comparisons of the alternative courses of action; develop ways of communicating the results effectively, not only to other systems analysts, but also to persons in a variety of other communities of interest and responsibility; find ways of helping effectively in the administrative activities of implementation; and devise procedures and standards for evaluating the results of implemented courses of action. Throughout the work, the analyst must be in close contact with his client.

In these lists of steps and activities in the systems-analysis process, one can see much of the classical positivist view of science and its method, but he can also see it greatly extended, this latter fact being very important for the future growth and acceptance of systems analysis.

To summarize, the central goal of the systems analyst, based on his understanding of the systems he has been studying, is to bring his results to bear on the functions of complex operating systems in society with a view to improving them; he helps those with relevant interests and responsibilities to change these functions beneficently. His analysis activities are aimed at assuring himself and others, to the extent possible, that the changes will have desired results.

However, he must pursue his purposes under important limitations and difficulties:

● Even though the analyst may dream of considering a system so large as to include within it all of the factors important to his problem, more practical considerations force him to set reasonable boundaries so that the work can be completed and reported on a schedule that will make its findings effective. Whatever the scope of the system he studies, large or small, it is a subsystem of a larger system, which creates difficulties at the boundaries.

● The system he studies is tied to an ongoing process of some sort in society that cannot be isolated for analysis, and therefore must be dealt with in vivo, with many conflicting vested interests watching the analysis and its results. Since this setting denies the analyst the privilege of a secret burial of his mistakes, one of the hallmarks of systems analysis today is a literature of strong criticism (23), good for the progress of the field, but perhaps misleading in its net public impact.

● Further--and perhaps most unsettling from the current conservative view of science and its role in society--he must work as part of the system that his results may change.

What can be said, then of the current state of the science of man/ machine operating systems? It is well founded, active, and growing in size and importance (24). The cornerstone science of operations research has advanced to a state of significant maturity, with its underlying theories advancing, the scope and variety of problems it deals with expanding, and the effectiveness of its findings growing in importance. However, systems analysis, still in an earlier, more formative stage of development, faces important, largely unsolved, difficulties:

1. The first is the very practical one of scale of effort and institutional support. Clearly, if large-scale problems are to be tackled with interdisciplinary teams, such teams must be available, and administrative arrangements must

exist for them to work together closely, conditions that seldom exist today, even in large US government bureaus (25). However, there is a notable exception on the international scene that should be mentioned: the International Institute for Applied Systems Analysis in Laxenburg, Austria, a nongovernmental research institute founded in 1972 and today supported by seventeen countries from both East and West, brings together scientists from more than twenty countries to conduct analyses on important international problems (such as those of energy and food).

2. The second difficulty is access to problems and the information bearing on them. To the worker in a classical science this may seem instinctively surprising, until he recalls the number of institutions and administrations involved with such problems as those of energy, and realizes that all have information that may be relevant and that many may have to be influenced by the systems analysis if the results are to be effective. Unless there is cooperative access and active participation in the work—sometimes forthcoming and sometimes not—the systems analysis is handicapped, perhaps fatally.

3. The US science establishment's current widely held philosophy of science—epitomized by the dichotomy "pure" and "applied"—is quite inadequate for systems analysis, which quite clearly is inseparably both, in the best traditions of science's long history.

4. The last difficulty is the lack of a code of good practice, widely accepted by both the public and the community of science, to guide science's attempts to influence public policy and to give the public a fair and realistic concept of what to expect from science and systems analysis (26).

The Challenge of Systems Analysis

The urgency for developing systems analysis arises from the imperatives of society's problems: they call for the sort of approach that systems analysis represents. It is in the name of these urgent social problems that systems analysis extends its challenge to all of science:

● The problems to be addressed are some of the most important of our age--and involve systems for which our thoroughly inadequate understanding must be improved, an improvement to which all sciences will be called on to contribute.

● The work of operations research analysts, even in the short history of their subject, assures us that the difficulties to be overcome by systems analysis are intrinsic and important, and will call forth the greatest scientific ability and ingenuity; the result will be important new science and significant applications.

● Since the goals and objectives of society and its subsystems are essential ingredients in a systems analysis, as we have seen, the spokesmen for these ideas (our literary men, political leaders, and philosophers) must become involved, thus offering science the naturally created opportunity-- indeed, the obligation--of forming a union, not only of the sciences, but also with the arts, in the common enterprise of improving the lot of mankind.

● The commonly accepted philosophy of science today must expand and mature to encompass systems analysis activities as an expression of scientific work. Leading thinkers in this field today (27) assure us that this is a natural extension of the classical activities of science and its philosophy, as well as a reasonable outgrowth of the philosophy of science as it has been developed in recent years.

Many of the operations and systems analysis workers in the United States gather at the semiannual joint meetings of the Operations Research Society of America and The Institute of Management Sciences. In addressing one of these meetings on October 16, 1979, Herbert A. Simon, who won the 1978 Nobel Prize in economics, hailed it as "a celebration of human rationality." The challenge to science and society is to enlarge this celebration to include the rational management of all of society's systems and their problems.

References and Notes

1. For a brief authoritative account by a participant, see Harold Larnder, in K. B. Haley, Ed., Operational Research '78 (North-Holland, Amsterdam, 1979), p. 3.

2. For a condensed account of the early events in this spread of activity, together with references to fuller treatments, see Hugh J. Miser, in (13) Volume 1, p. 3.

3. This memorandum is included in P. M. S. Blackett, Studies of War: Nuclear and Conventional (Hill and Wang, New York, 1962), p. 171.

4. Although most of the military operations research in World War II dealt with air and naval operations, ground combat can also exhibit aspects of regularity. For example, the battle for Iwo Jima in 1945 progressed in accordance with a simple theory; see J. H. Engel, Operations Research 2, 163 (1954).

5. Philip M. Morse and George E. Kimball, Methods of Operations Research (National Defense Research Committee, Washington, D. C., 1946), p. 7. Also published by Wiley, New York, 1951.

6. As described in John G. Kemeny, A Philosopher Looks at Science (Van Nostrand Reinhold, New York, 1959), especially Chapter 5.

7. For accounts of early work in agriculture, retailing, and automobile traffic now regarded as classic, see, respectively: C. W. Thornthwaite, Operations Research 1, 33 (1952-1953); Horace C. Levinson, Operations Research 1, 220 (1952-1953); Leslie C. Edie, Operations Research 2, 107 (1954).

8. See, for example, the issues over the last decade of the journals Operations Research, Management Science, The Journal of the Operational Research Society, and Interfaces (this last being an especially rich source of business examples).

9. See Eric Brodheim and Gregory P. Prastacos, Interfaces 9, no. 5, 3 (1979). At the May 1, 1979, meeting of The Institute of Management Sciences and the Operations Research Society of America in New Orleans, this work received the eighth annual Management Science Achievement Award sponsored by the TIMS College on the Practice of Management Science. The quotations are from this paper for the most part, but some have been amplified by

Gregory Prastacos in order to make this condensed account relatively complete (his assistance in this regard is gratefully acknowledged, as is the permission from Interfaces to use the material from this journal). The quotation from Johanna Pindyck is from a letter included in Brodheim and Prastacos, loc. cit.

10. See Gregory P. Prastacos and Eric Brodheim, PBDS: A Decision Support System for Regional Blood Management, Report 80-01-01, Department of Decision Sciences, The Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania 19104; to appear in Management Science.

11. For an introduction to search theory and its literature, see Bernard O. Koopman, Amer. Math. Monthly 86, 527 (1979).

12. Philip M. Morse, Operations Research 1, 164 (1952-1953).

13. Joseph J. Moder and Salah E. Elmaghraby, Eds., Handbook of Operations Research: Volume 1, Foundations and Fundamentals, and Volume 2, Models and Applications (Van Nostrand Reinhold, New York, 1978).

13a. For some of the more recent work on heuristic techniques, see Gerard Cornuejols, Marshall Fisher, and George Nemhauser, Management Science 23, 789 (1977), and Richard Karp, Math. of Opns. Res. 2, 209 (1977). These two papers shared the 1977 Lanchester Prize of the Operations Research Society of America. For some earlier references, see Herbert A. Simon and Allen Newell, Operations Research 6, 449 (1958).

14. See (13), Volume 2, for concise summaries of work in each of these areas.

15. See (13), Volume 2.

16. The program of any recent semiannual joint meeting of the Operations Research Society of America (ORSA) and The Institute of Management Sciences (TIMS) offers an instructive view of the current concerns and activities of the profession.

17. Indeed, the US societies representing the two communities of interest, ORSA and TIMS, now hold their semiannual meetings in the US jointly, share several publications, and have many joint activities.

18. Peter C. Belford and H. Donald Ratliff, Operations Research 20, 619 (1972). The quotations and Figure 3 are from this paper and are reproduced by permission.

19. Personal communication from H. Donald Ratliff, January 22, 1980.

20. This use of the term systems analysis is not to be confused with the meaning common in computer-application activities.

21. As a recognition of this fact, much of what I call here systems analysis is sometimes called "policy science" or "policy analysis."

22. A classic military systems analysis is described briefly in nontechnical form in Bruce L. R. Smith, The Rand Corporation: Case Study of a Nonprofit Advisory Corporation (Harvard University Press, Cambridge, 1966), Chapter VI. For a short account of a major study for the New York City Fire Department, see Edward J. Ignall et al., Interfaces 5 (Part 2 of no. 2), 48 (1975); for a fuller account, see Warren Walker, Jan Chaiken, and Edward Ignall, Eds., Fire Department Deployment Analysis: A Public Policy Case Study (Elsevier North-Holland, New York, 1979). For a short account of a study of transport in the Sudan, see Thomas L. Saaty, Interfaces 8 (Part 2 of no. 1), 37 (1977). For an account of a study for the Netherlands government, see B. F. Goeller et al., Protecting an Estuary from Floods--A Policy Analysis of the Oosterschelde, R-2121/1-NETH (The Rand Corporation, Santa Monica, California, 1977). For a general introduction to systems analysis, see E. S. Quade, Analysis for Public Decisions (American Elsevier, New York, 1975); a three-volume Handbook of Systems Analysis is in preparation at the International Institute for Applied Systems Analysis, Laxenburg, Austria. For a short introduction aimed at developing countries, see Systems Analysis and Operations Research: A Tool for Policy and Program Planning for Developing Countries (National Academy of Sciences, Washington, 1976). The literature sometimes contains accounts of techniques employed in systems analyses; for example, for a survey of models used in energy policy studies, see Alan S. Manne, Richard G. Richels, and John P. Weyant, Operations Research 27, 1 (1979).

23. See, for example: Ida R. Hoos, Systems Analysis in Public Policy: A Critique (University of California Press, Berkeley, 1972); Garry D. Brewer, Politicians, Bureaucrats, and the Consultant (Basic Books, New York, 1973); Martin Greenberger, Matthew A. Crenson, and Brian L. Crissey, Models in the Policy Process: Public Decision Making in the Computer Era (Russell Sage Foundation, New York, 1976); Giandomenico Majone and E. S. Quade, Pitfalls of Analysis (Wiley, Chichester, England, 1980).

24. If we take professional society membership as an indicator of interest and at least some activity, the operations and systems research community consists of about 10,000 persons in the US and Canada, and 25,000 to 35,000

world wide. The work of this community is reported in some 35 central journals (see (13), Volume 1, pp. 17-18) and an internationally sponsored comprehensive abstracting journal, International Abstracts in Operations Research (North-Holland, Amsterdam), currently in its twentieth year of publication.

25. For a 1972 view of the situation in the US federal government, not much changed since, see Hugh J. Miser and W. Edward Cushen in Michael J. White, Michael Radnor, and David A. Tansik, Eds., Management and Policy Science in American Government (Lexington Books, Lexington, Mass., 1975), p. 23.

26. The Operations Research Society of America made an attempt in 1971 to address this issue; the result was widely debated, but does not appear either to have had lasting influence or to have generated a more refined or general flow of thinking leading to generally accepted principles. For some of the items of the literature, see Thomas E. Caywood et al., Operations Research 19, 1123 (1971), and later correspondence in Operations Research 20, 205 (1972); the 1972 and 1973 issues of Minerva carried a series of relevant essays; see also Management Science 18, B608 (1971).

27. See, for example: Hylton Boothroyd, Articulate Intervention (Taylor and Francis, London, 1978); C. West Churchman, The Systems Approach and its Enemies (Basic Books, New York, 1979); and Giandomenico Majone, "Policies as Theories," to be published in Omega, the International Journal of Management Science, and "The Craft of Applied Systems Analysis," to appear.

Figure Legends

Figure 1. Inventory levels and mean daily demands for blood units for given availability rates at hospital blood banks.

Figure 2. Illustration of a planned regional blood flow.

Figure 3. Assignment of student locations to schools for the high schools of Gainesville, Florida.