HANDBOOK OF SYSTEMS ANALYSIS

VOLUME 1. OVERVIEW

CHAPTER 3. EXAMPLES OF APPLIED SYSTEMS ANALYSIS

Edward S. Quade

October 1981
WP-81-133

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

The International Institute for Applied Systems Analysis is preparing a Handbook of Systems Analysis, which will appear in three volumes:

- Volume 1: Overview is aimed at a widely varied audience of producers and users of systems analysis studies.

- Volume 2: Methods is aimed at systems analysts and other members of systems analysis teams who need basic knowledge of methods in which they are not expert; this volume contains introductory overviews of such methods.

- Volume 3: Cases contains descriptions of actual systems analyses that illustrate the diversity of the contexts and methods of systems analysis.

Drafts of the material for Volume 1 are being widely circulated for comment and suggested improvement. This Working Paper is the current draft of Chapter 3. Correspondence is invited.

Volume 1 will consist of the following ten chapters:

1. The context, nature, and use of systems analysis
2. The genesis of applied systems analysis
3. Examples of applied systems analysis
4. The methods of applied systems analysis: An introduction and overview
5. Formulating problems for systems analysis
6. Objectives, constraints, and alternatives
7. Predicting the consequences: Models and modeling
8. Guidance for decision
9. Implementation
10. The practice of applied systems analysis

To these ten chapters will be added a glossary of systems analysis terms and a bibliography of basic works in the field.

Hugh J. Miser
IIASA
A-2361 Laxenburg
Austria

12 October 1981

CONTENTS

1. INTRODUCTION 1

2. IMPROVING BLOOD AVAILABILITY AND UTILIZATION 3

Background 3

Approach 5

Analysis 7

Implementation 13

Computer modules 16

Impact 17

3. IMPROVING FIRE PROTECTION 18

Background 18

Origin of the project 19

Analysis 21

Recommendations of the project team 27

History of the implementation 29

Evaluation 31

4. PROTECTING AN ESTUARY FROM FLOODING 32

Background 32

The analytic approach 36

Methods for synthesizing and presenting results . 39

Conclusions 52

The decision 55

5. PROVIDING ENERGY FOR THE FUTURE 56

Demand 58

Supply 60

System properties 62

REFERENCES 66

CHAPTER 3. EXAMPLES OF APPLIED SYSTEMS ANALYSIS

Edward S. Quade

1. INTRODUCTION

Applied systems analysis, while not a completely new idea, has been practiced for a relatively short time. Many people are not aware of the kinds of issues on which it might be employed, of the results that can be expected, or of the resistance its most logical results can meet from the people affected. Examples and case histories are a way of alerting the public to the advantages and drawbacks of a systems approach to decisionmaking, particularly when applied to public decisions outside the military or industrial context.

Analysts may also profit from reviewing examples. The craft of systems analysis is not easy to master. Often the analyst must take actions important to the success of his study that do not appear to be a step in any systematic way of describing the process of carrying out such a study -- the sort of thing that comes from practical experience. The review of examples and case studies is, to a limited extent, a substitute for practice, although an inadequate one. Examining cases can also help to make clear some of the compromises with mathematical and scientific exactitude that are often needed to make progress, compromises forced not only by the pressure of time or the need to win acceptance for the work, but also because without them the mathematics might be beyond our capabilities.

Each of the examples presented in this chapter emphasizes different aspects of the analytic process, the arrangement being roughly in the order of increasing difficulty.

In the first case the problem was clearly defined, and an adequate measure of effectiveness was available, one that the decisionmakers, a small group of professionals, relatively free from political pressure and sympathetic to the use of analysis, did not question. The approach, although it required imagination to design, made use of well established mathematical models. Our attention here is on the means to obtain a demonstrably superior solution and its smooth implementation.

The second case deals with a situation in which the process of converting the results of analysis into changes in operations was more difficult and time consuming than the process of performing the analysis. Here the decision as to what action to take had to be made on the basis of a proxy or surrogate measure of effectiveness, using crude models of recent design, thus leaving room for argument and disagreement by those whose special interests were threatened.

The third case involved a major decision affecting an entire country in which a choice had to be made among strategies, no one of which was clearly superior to any of the others in all respects. Here the major attention is to the method by which the results were presented to the decisionmakers, legislators, mostly without analytic training, representing constituencies with widely varied interests. who had to choose their action in an intensely political situation. It is also typical of the type of problem in which there is no direct empirical verification that the choice made is best, or even adequate.

The fourth case is concerned with a critical global problem, i.e., one whose concerns cut across national boundaries and for which no solution can be successfully implemented without cooperative joint action. In contrast to the previous cases, while the analysis demonstrated that solutions exist, owing to the nature of the decisionmaking situation it was unable to provide more than general guidelines for obtaining good decisions. The study results offer a way to focus the hundreds of decisions, possibly otherwise uncoordinated, required during the next few years to resolve the issue of achieving a globally sustainable solution.

In preparing the descriptions of the several case studies that follow, we have made no effort to distinguish between the material written and published by the analysts responsible for the studies and that inserted or modified by the author of this chapter. Most of the material is, in fact, taken almost verbatim from the original reports and other publications. We do this, of course, with the permission of the original authors and the copyright holders.

2. IMPROVING BLOOD AVAILABILITY AND UTILIZATION

Background. Blood is a living tissue of unique medical value. It is the vehicle that carries oxygen, nutrients, and chemicals to all parts of the body, and carries away waste products. It appears in 8 major blood types whose frequencies vary from 38% (O+) to 0.5% (AB-) in the human population. It is composed of several components (red cells, white cells, platelets, plasma), all of which can be extracted from whole blood through appropriate procedures. Each of these components serves a separate function in the human organism, and has a different use in its medical treatment. All of these components are perishable, with their lifetimes varying from 24 hours (platelets) to 21 days (red cells). Whole blood and red cells, both of which have a lifetime of 21 days, together account for more than 95% of the transfusions that take place in the US today. The 21 days is currently a legally defined lifetime in the United States, after which the blood has to be discarded.

Blood is collected in units of one pint per donor at collection sites such as a Regional Blood Center (RBC), a Hospital Blood Bank (HBB), or a mobile unit. When collected it undergoes a series of typing and screening tests and, once processed, if needed (i.e., frozen or separated into components), it is shipped to a Hospital Blood Bank to be stored and be available to satisfy demands for transfusions.

The Hospital Blood Bank operates as a storage and issuing agency. During the course of a day the Blood Bank receives a random number of transfusion requests for each blood type, each request for a random number of units. Once a request for a patient is received, the appropriate number of units of that type are removed from free inventory and upon successful crossmatching they are placed on reserve inventory for this particular patient. Any of these units that are not transfused are returned back to free inventory. *Demand* is defined to be the number of units requested, and *usage* to be the number of units transfused. Any units that are not used within their lifetime are considered *outdated* and are discarded from inventory.

Historically, HBBs have generally maintained high inventories of most of the 8 different types of each blood product in order to provide high availability to satisfy patient needs and have accepted the low utilization resulting from spoilage. In 1974, the national utilization rate of whole blood and red blood cells prior to expiration was estimated to be only 80%. At that time, the federal government adopted a national blood policy that called for an all-volunteer blood supply to be accessible to all segments of the public. The blood supply was to be efficiently administered through forming regional associations of blood service units in each of which a RBC and the HBBs that it serves would collaborate to achieve these objectives.

Each year over two million hospitalized Americans depend on 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 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 (GNYBP), the largest in the world, puts it, "We face the major problem of how to maximize 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". [1]

In 1979, Eric Brodheim of the New York Blood Center and Gregory P. Prastacos of the University of Pennsylvania reported a study that goes a long way toward providing a solution to many problems of blood distribution and utilization. The description of their study which follows, together with the background above, is taken almost verbatim from their reports [1], [2]. Management science and operations research techniques had previously been the basis of much work on blood management; Prastacos cites 69 references in [2].

Approach. The complexity of the blood distribution problem is primarily due to blood's perishability, to the uncertainties involved in its availability to the RBC, and in the demand and usage for it at each of the HBBs. Superimposed on this are the 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 red blood cells.

Since blood, by US national policy, is derived from volunteer donors, its availability is uncertain and is a function of factors that cannot be controlled by the RBC. The demand and usage of blood at HBBs are also uncertain and vary from day to day and between hospital facilities. The HBBs within a region may range from those transfusing a few hundred units to those transfusing tens of thousands of units per year. The most frequently occurring blood type (O positive) occurs in approximately 39% of the population, while the least frequently occurring blood type (AB negative) occurs in only about 0.5% of the population. While most medical authorities agree that at least 90% of all blood transfusions could be in the form of red blood cells, some hospitals transfuse almost entirely red blood cells while others transfuse entirely whole blood, with the ratio of whole blood to red blood cells frequently changing with time as transfusion practices improve.

The national blood transfusion service is characterized by diversity. Each RBC has independently evolved its own philosophies and techniques for blood distribution. Each region strives for self-sufficiency in supplying the blood needs of the hospitals in its region from donors who also reside in approximately the same area. Because of these factors, it is essential that any strategy devised be defensible from the point of view of both the RBC and each of the wide range of HBBs that it serves. Furthermore, any strategy that involves interactions between RBCs must provide for clearly defined benefits for all participants. Some objectives conflict (e.g., availability vs. utilization of blood at an HBB) and costs are involved 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, resulting in low utilization and much spoilage.

After becoming thoroughly familiar with the practical operations of the Long Island blood distribution system, which was to be 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:

(i) 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 efficiently. This calls for some form of centralized decisionmaking at the RBC, which will operate under objectives of overall regional efficiency, as opposed to the existing mode of decentralized decisionmaking, operating under objectives of local (i.e., HBB) efficiency.

(ii) 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.

(iii) It is 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 planning operations and utilizing resources.

Analysis. The blood needs of an HBB can be expressed in terms of the ***demand*** for blood (i.e., the number of units required to be on hand for possible transfusion) and the ***usage*** of blood (i.e., the number of units transfused). A model is required that translates demand and usage to availability and utilization as functions of the RBC blood distribution policy and the HBBs' blood stocking policy. Such a model was established by a combination of statistical analysis and Markov chain modeling; it was then used to derive regional allocation strategies with desirable properties regarding availability and utilization.

The availability rate (i.e., fraction of days when the inventory of a given blood type on hand is sufficient to meet the demand) at an HBB depends only on the statistical pattern of demand and the total inventory level. To establish this relation data were collected on the daily demands for each blood type at a number of HBBs. These data, together with comparable information published by other researchers, provided a total of 49 data sets, each set containing the daily demands for one blood type at one HBB over a period of at least six months.

Statistical analysis established a "universal" piece-wise linear relation between inventory level and mean daily demand, with availability rate as a parameter, shown in Figure 3.1. Additional tests showed that the model could predict the availability rate to within approximately 10% of actual experience for availability rates in the range of 80% to 99%.

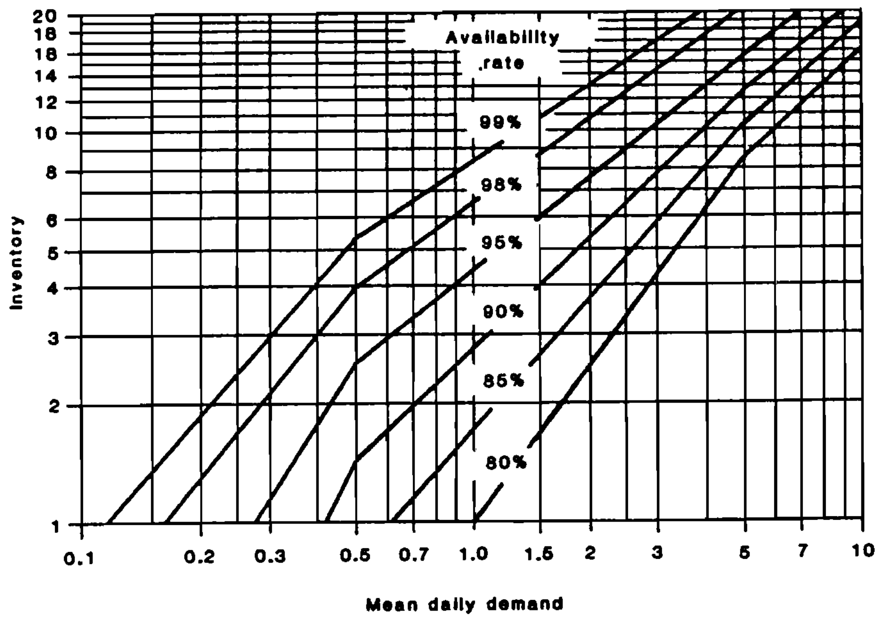

Figure 3.1. Inventories and mean daily demands for blood units for given availability rates at hospital blood banks. Source: Brodheim and Prastacos (1979).

The acceptable range of availability rates for HBBs was then established by requesting a number of HBBs to provide concurrent estimates of their mean daily demand and the inventory levels in each of the 8 blood types that they considered adequate. In almost all cases, the levels that the HBBs considered adequate turned out to correspond to availability rates of between 90% and 95%.

It was similarly established that the daily usage could be modeled as a mixture of a Poisson and a triangular-type distribution whose parameter is related to the mean daily usage. These analyses showed that the parameters for the models of demand and usage could be readily estimated from records maintained by HBBs and further that availability rate could be estimated reliably by the model.

The utilization rate (i.e., the fraction of the supply that is transfused) 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.

The utilization rate model is illustrated for a fixed utilization rate of 98% by the family of broken lines in Figure 3.2, where the scheduling factor ρ is the fraction of mean daily usage that is replaced by retention shipments. As an example, if an HBB's mean daily usage for a given bood product is 1.5, then the HBB can achieve a utilization rate of 98% by any of the following combinations: desired inventory $I = 1$ and $\rho = 0.89$, or $I = 3$ and $\rho = 0.82$, or $I = 5$ and $\rho = 0.70$.

It was shown that this stocking procedure maintains the mean inventory close to this desired inventory level most of the time. It was also shown that adding additional stages of returns and redistribution would make only slight improvements in the availability and utilization rates achieved. Since multiple redistributions introduce severe logistical problems and significant transportation costs, distribution strategies involving more than two stages of distribution were not investigated.

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 that 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 nona-

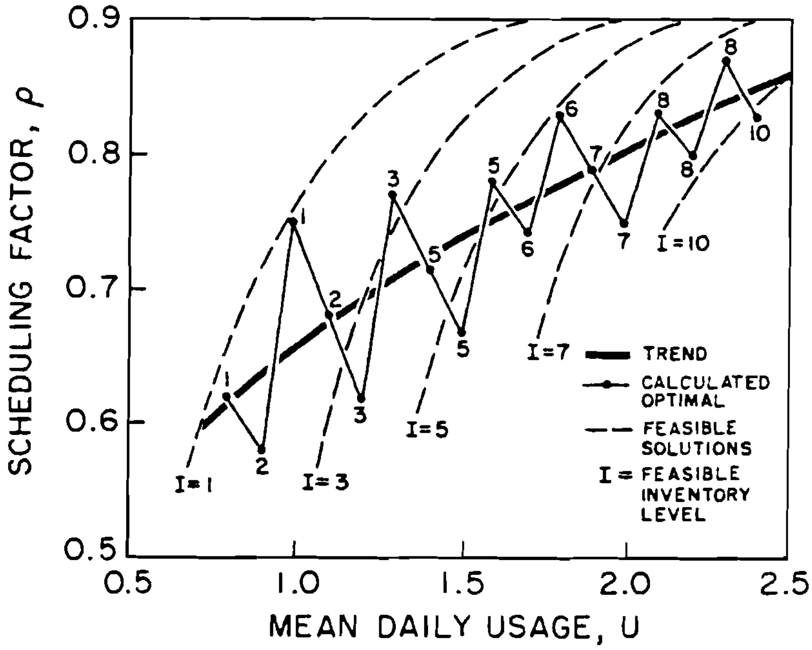

Figure 3.2. For various mean daily usages U, the combinations of inventory level I and scheduling factor ρ (the fraction of mean daily usage that is replaced by retention shipments) that will achieve a utilization rate of 98%. Source: Brodheim and Prastacos (1979).

vailability and nonutilization risks among hospitals regardless of their relative size, and is consequently a highly defensible policy.

Finally, it was shown that the highest possible regional availability and utilization rates are achieved when the desired inventory level for each blood type in each HBB is at the value that minimizes the total number of rotational units that are required to achieve these availability and utilization rates.

It is a straightforward effort by computer to calculate the combination of inventory level and scheduling factor that requires the minimum number of rotational units. The minimum number of rotational units required to achieve a fixed utilization rate of 98% and an availability rate of 95% are indicated by the points connected by the straight line segments in Figure 3.2. The irregular behavior of this solution is due to the fact that inventory levels must be integer values and rounding occurs on very small values. As an example, the minimum rotational shipments required to an HBB of mean usage of 1.5 units daily to obtain the target goals above occur when the desired inventory is 5 units, and the scheduling factor is set to 0.67. The trend line which is drawn in the heavy line in Figure 3.2 is meant to indicate simultaneously the optimal values in inventory level and scheduling factor for given values of mean usage.

Next, various operational considerations were taken into account. One of these was the need to equalize the mix of fresh to older bloods between HBBs. Another was to standardize the delivery interval. It was determined that, for blood types where mean daily usage is small, the mean required number of units on rotation is independent of whether the delivery interval is one, two, or four delivery days. For higher values of mean daily usage, the difference between one-day and two-day delivery intervals remains slight, but increasing the delivery interval to four days causes significant increases in the mean number of rotational units required to achieve the policy objectives.

As a result of these observations, HBBs that transfuse less than approximately 1,500 units per year are receiving deliveries every four delivery days. Since analyses showed little distinction in the number of rotational units required between one-day and two-day intervals between deliveries, all larger HBBs were encouraged to utilize two-day intervals between shipments.

The final model was then formulated as a mathematical program. The decision variables determined by the program are the distribution parameters: size of rotation and retention shipments, frequency of deliveries, and desired inventory levels for each HBB.

The objective of the program is to achieve the set target values for availability and utilization rates, while conforming to the operational constraints, with the minimum possible amount of total fresh rotational blood needed in the region. Even though the model is highly nonlinear, its structure is decomposable, and the optimal solution is readily obtained by parametric enumeration.

Implementation. The analysts then turned to the task of implementation in their test region, the Long Island Blood Services distribution system (LIBS). LIBS is approximately the median size of existing regional associations and processes approximately 100,000 units of blood per year. It serves a diverse area ranging from the rural parts of Suffolk County to urban parts of New York City with 34 hospitals and a combined population of two million persons. LIBS is one of four divisions of the GNYBP, which serves approximately eighteen million people in the greater New York area. This facilitates interaction between these regions for such purposes as to smooth out local short-term shortages and surpluses.

The implementation of the program was carried out in a series of planned stages. At first only four hospitals were invited to join the program. They were provided support to correct rapidly the start-up problems that occurred. Once these HBBs were working to the satisfaction of their supervisors, they described the system to supervisors of other HBBs at seminars where the operations research staff, wherever possible, played the passive role of providing information when requested to do so. Responding to this approach, all but four very small HBBs in Long Island voluntarily joined the program over a two-year period and none have dropped out.

A major advantage of the Programmed Blood Distribution System (PBDS), both to the RBC and to the HBBs, is the ability to preschedule most deliveries. Prior to PBDS being implemented, a number of delivery vehicles were dispatched as orders came in. For urgent orders, vehicles were dispatched immediately, while for more routine orders an attempt was made to hold vehicles back until several deliveries in the same geographical area could be combined. This procedure was expensive and, perhaps more importantly, resulted in situations where even urgent orders were delayed, since delivery vehicles were not always available during peak delivery hours.

With the PBDS most deliveries are prescheduled, and take advantage of known traffic patterns in order to minimize delivery time. An interactive, computer-aided procedure was devised that assigns HBBs to delivery routes so as to meet their time and frequency-of-delivery requirements. The twelve- delivery- day planning cycle is split into three groups of four delivery days, after which the delivery cycle repeats. In each four-delivery-day cycle each HBB receives either one, two, or four deliveries. The procedure tries to satisfy the delivery requirements without leaving gaps in consecutive time slots, since an empty time slot indicates idle time.

An opportunity to test the flexibility of this delivery scheme occurred recently when the LIBS Blood Center was moved from one location to another several miles away. It was found that the delivery routes could be adjusted rapidly and the required reassignment of the HBBs was determined conveniently.

The resulting regional blood flow is illustrated in Figure 3.3. In this figure the aging of the RBC inventory is indicated down the center of the figure with the scheduled movement of blood to HBBs indicated to the left of the figure and the nonscheduled movement to the right. The long-dated, stock-dated, and short-dated RBC inventories refer to blood units that are suitable, respectively, for rotation shipments, for retention shipments, and solely for supplemental shipments--which are filled by the oldest available units. The arrows indicate a

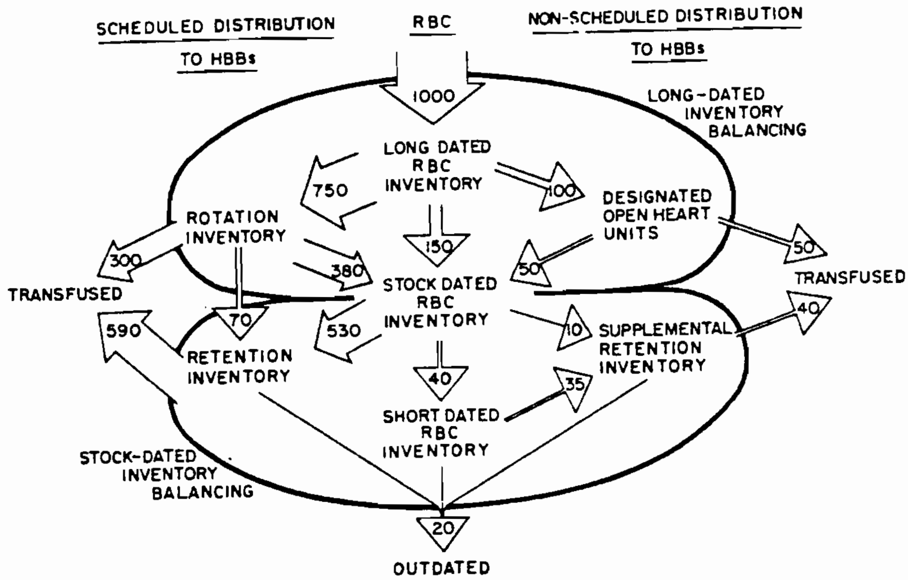

Figure 3.3. An illustration of a planned regional blood flow based on the presumption that 1000 units are collected and distributed. Source: Brodheim and Prastacos (1979).

blood flow that is normalized to 1,000 units collected.

On the basis of this anticipated regional blood flow, the RBC's inventory is evaluated and adjusted daily. Stock-dated inventory balancing is performed late each afternoon after all rotational returns have been received. It involves the part of the flow circled toward the bottom of Figure 3.3. The available stock-dated inventory is compared to the retention shipments that are scheduled, and the anticipated supplemental shipments, plus a small reserve for unusual circumstances, which is shown as becoming short-dated inventory. When the inventory for any product exceeds these requirements, the excess units are designated as surplus, and transshipped to the New York Blood Services (NYBS) division of GNYBP. When stock-dated inventory is below requirements, then either surplus long-dated units (if available) will be retained, or the shortage will be made up from the other divisions of GNYBP if possible.

Long-dated inventory balancing is performed each morning after the bulk of the blood collected the previous day has been typed. It involves the part of the flow circled at the top of Figure 3.3. The long-dated regional inventory that is expected to become available during the day is compared to the commitment of units for scheduled rotation shipments plus units required to meet open heart surgery needs (which is a specialized procedure where only fresh blood units are suitable). Any units in excess of these requirements are either retained to make up for shortages in stock-dated inventory as discussed above, or are made available for transshipment to other divisions of GNYBP. Since LIBS collects in excess of its needs, there is generally a surplus of rotation units, especially of the more common blood types.

Computer Modules. To improve its effectiveness and transportability, PBDS has been computer- coded in three basic modules: policy selection, distribution schedule, and control procedure. Each of these modules has a special purpose in the implementation and operation of PBDS in a region, and each can be addressed interactively by the user (RBC director or distribution manager) in order to determine or evaluate strategic or tactical decisions in blood management.

The policy-selection module is run first. It uses the region's data on the demand and usage patterns of the HBBs, together with the models outlined earlier, to produce a policy- selection table. This table presents the decisionmaker with alternative targets (shortage rate, outdate rate, scheduling factor) that can be obtained for different levels of blood supply in the region.

Once targets are selected, they are put into the second model, which handles distribution scheduling. The output of this module is a detailed schedule of the shipments of rotation and retention blood for each blood type that each HBB will receive on each delivery day. These schedules are communicated to the HBBs for comment and feedback. Once this phase is completed, the PBDS operation can begin.

Finally, in order to detect possible changes in the needs of the HBBs, a series of hypotheses tests are run every two weeks as a control procedure. If a change is detected, new estimates are made and new distribution schedules are computed. In this way the RBC keeps its data and operations an up- to- date reflection of the changing patterns of blood needs and usages in its region.

Impact. The impact of PBDS can be most directly measured in terms of improvement in blood utilization. Prior to the implementation of PBDS, the utilization rate in the LIBS region was 80%, which was also then the national average. Since the implementation of PBDS, the utilization rate for LIBS has improved by 16%, while the national average has improved little if at all during the same interval. The improvement in utilization at LIBS translates to 80% reduction in wastage, and therefore, to an annual saving of $500,000 per year.

Of lesser economic impact is the reduction in the number of deliveries. Before PBDS was implemented, an average of 7.8 weekly deliveries were made to each hospital, all of which were unscheduled; after PBDS was implemented, the number of deliveries dropped to 4.2, but of which only 1.4 were unscheduled. By associating a cost of $10 to an unscheduled delivery to an HBB and a $5 cost to a scheduled delivery (which is part of a route), PBDS has achieved a 64% reduction in delivery costs. This translates to an annual cost saving of $100,000. Additional important, though less tangible, cost savings are achieved by implementing sounder blood banking practices to reduce discrepancies between actual and achievable performance for individual HBBs.

Probably the most important saving in the national health care bill brought about by PBDS is realized by improved blood availability to patients. Since deliveries to the hospitals are mostly prescheduled, elective surgeries can also be prescheduled so as to minimize the number of surgeries postponed because of lack of the right blood products. However, savings from this improved availability are extremely difficult to estimate and quantify.

3. IMPROVING FIRE PROTECTION

Background. How many fire companies to support, where to locate them, and how to dispatch them are important questions for US cities as fire incidence increases (Fig. 3.4) and inflation shrinks their budgets. Between 1969 and 1975 many new techniques were developed at the New York City-Rand Institute to help resolve these questions [4]. This case describes a fire department deployment study carried out in Wilmington, Delaware, by a local project team with technical assistance from the New York City-Rand Institute [7], [8].

Wilmington is the largest city in Delaware. It has large concentrations of the poor (in 1969, 16 percent of all its families had incomes below the poverty level), the aged, and minority groups (44 percent nonwhite), all with greater-than-average needs for public service to be paid for from a declining tax base. Although a shipping and transportation center, Wilmington's economy has shifted away from manufacturing to executive offices and service industries. Its operating budget for fiscal 1978 (excluding education) was $27,796,641, or $346 per capita.

The Wilmington Bureau of Fire (the official name of the department) is administered by the Chief, who reports to the Commissioner of Public Safety. The Chief is appointed by the Mayor, usually from within the Bureau and on the basis of merit, tenure, and experience. The Bureau is the only fully paid fire department in Delaware.

Origin of the project. Of the eight firehouses in Wilmington in February 1973, only one had been built after 1910. The exception was the result of a 1967 study conducted by the city's Department of Planning and Development, which concluded that not one, but seven new firehouses should be built, and that one of the old houses should be renovated. After the first firehouse was built, however, the architect predicted a substantial overrun on the second one. The study had projected $304,000 for this house, and $475,000 was actually allocated in the 1972 and 1973 capital budgets, but the new cost figure was more than $700,000.

In addition, the new Mayor questioned the overall adequacy of the city's fire protection and his newly appointed Chief raised questions about the firehouse locations recommended by the 1967 study. Together, all these considerations led to an administrative decision in August 1973 to suspend any new firehouse construction until a thorough analysis of the situation could be undertaken.

At this time Wilmington learned that the New York City-Rand Institute had a contract with the Office of Policy Development and Research of the US Department of Housing and Urban Development (HUD) to assist a number of cities in using methods developed at the Institute for analyzing the deployment of emergency service vehicles. The HUD contract had, among its objectives, to determine the usefulness of the methods and the ease with which understanding and the ability to use them could be transferred to city personnel. Wilmington applied to the Institute for assistance in determining where to locate the previously budgeted replacement firehouses.

Therefore an analysis was undertaken in February 1973 by a project team led by the Director of Program Analysis in Wilmington's Department of Planning and Development, with guidance provided by the New York City-Rand Institute staff. The primary objective was to evaluate, and to revise if necessary, the deployment study of 1967.

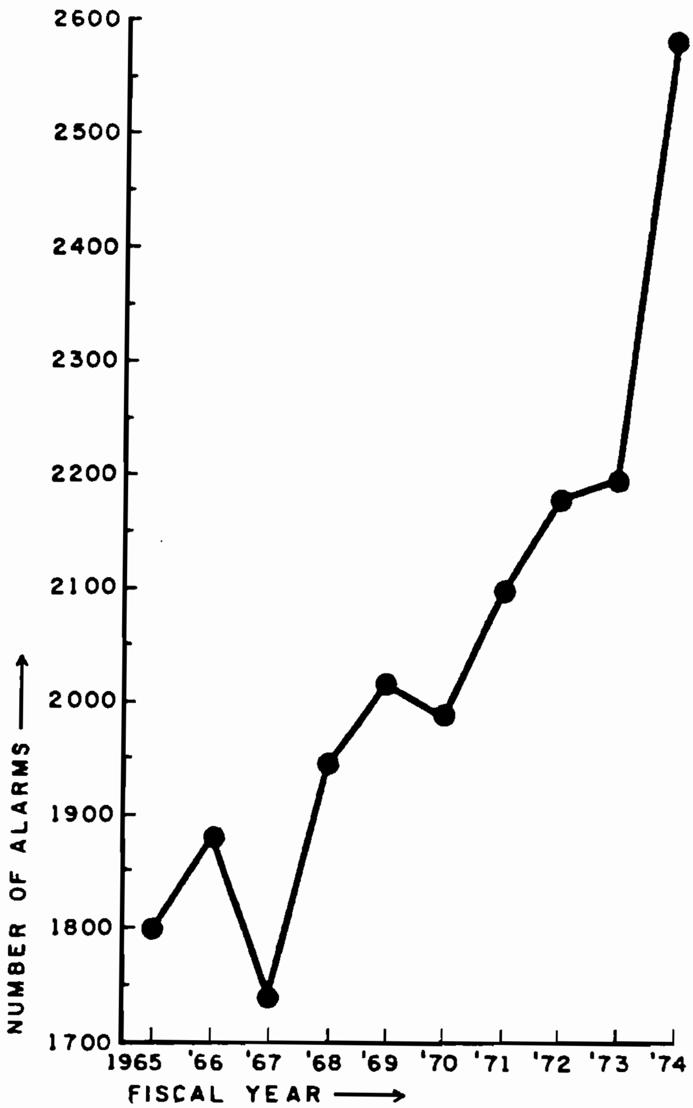

Figure 3.4. The total number of fire alarms, Wilmington, Delaware, 1965-1974. Source: Walker, Singleton, and Smith (1975).

Analysis. Fire protection is a basic municipal service. The size of the firefighting force and its distribution throughout a city impose important policy decisions on the city government. A policy that leads to rapid response with the appropriate firefighting resources can save lives and reduce property loss. The trouble is that there is little agreement on just what is "appropriate." In order to evaluate alternative deployment policies, both performance measures and models to use in calculating the values of the measures under different policies are needed. It is these measures and models that the New York City-Rand Institute supplied [8].

Since a fire department's primary objectives are to protect lives and safeguard property, the most important measures of its performance are the numbers of fire fatalities and injuries, and the value of property lost in fires. It is not possible, however, to use these measures to evaluate different deployment policies because there are as yet no reliable ways to estimate the effects that different policies have on them. For example, if the number of fire companies on duty were doubled (or halved), no one can say with a satisfactory degree of confidence what effect the change would have on the number of fire casualties or property losses. The direction of the effects on these measures may be predictable for large changes, such as doubling or halving, but the quantitative (practical) consequences are not--and in the case of more realistic small changes in deployment policy, neither the direction nor the size of the change in casualties or damage is predictable.

Therefore, in order to evaluate alternative firehouse configurations, three substitute, or "proxy," measures were used, the first two of which are directly related to loss of life and property damage: (1) travel time to individual locations, (2) average travel time in a region, and (3) company workload. Changes in firehouse locations have consequences that appear as changes in the values of these measures. The consequences can therefore be evaluated against the background of other considerations, such as hazards, fire incidence, costs, and political constraints.

Before these measures can be calculated, certain data must be collected and analyzed.

Most of the time, most fire companies are providing insurance against fires rather than engaging in actual firefighting. That is, they are available in case a fire occurs. This is important because, if a fire does occur, the department wants companies available close by so that they can get to the scene of the fire as quickly as possible. The degree of coverage given to any particular location in a city may therefore be measured by the expected travel time to that location from the nearest firehouse. Areas close to firehouses are considered well covered; those far away are considered poorly covered. Thus, one measure of the coverage in a region is the maximum travel time (or distance) from the nearest firehouse to any point in the region.

Actually, several travel times were considered in the test-city analyses. First, because engine and ladder companies perform different tasks at a fire, it is important to separate travel times by the type of company. In addition, since two units of the same type working together may be able to take some action that neither could perform alone, the travel time of each arriving apparatus is important. Therefore, one way of evaluating alternative arrangements of fire companies is to consider the set of travel times for the engines and ladders assigned to respond to each potential incident location.

It is rare for one deployment policy to produce travel times that are superior to those of another policy for each and every incident location, and a consideration of the changes in travel time to all incident locations would be an overwhelming task. Consequently, the comparison of alternative policies usually involves summary statistics such as the travel times to groups of incident locations. The location groups may be formed in several different ways--by region of the city or by company response area, for example. In Wilmington, the measures used were:

- The average travel time to all locations in the group (with each location having equal weight). This is a useful measure of the general coverage that a department provides for any type of incident.

- The expected travel time to a structural fire (taking into account the fact that some locations experience more structural alarms than others). This measure estimates the travel times that a department can expect to achieve to the fires that have the greatest potential for life and property loss.

- The maximum travel time to any incident location in the group.

In order to analyze alternative deployment policies, a way is needed to estimate travel times from firehouse locations to incident locations. There are several ways to do this. For example, one could develop a matrix containing the estimated travel times between all pairs of firehouse locations and incident locations. The method used in this study employed empirical data to develop a general relation between travel distance and travel time. Then, given the travel distance between any two points (which can be easily estimated from their grid coordinates), the travel time could be estimated.

Figure 3.5 shows the results of an experiment to gather the data needed to estimate travel time in Wilmington, Delaware. Five fire companies (two engines, two ladders, and a rescue squad) recorded the distance traveled and the travel time for 243 responses. The best estimates of travel time were obtained by using the relation:

$$\textit{travel time (minutes)} = 0.69 + 1.69 \times \textit{travel distance (miles)}$$

This model was used in a subsequent analysis of the deployment of Wilmington's fire companies. After the distance between a firehouse and an alarm box was estimated (using another model), the time required to travel this distance was estimated using the model. For example, if a travel distance was estimated to be one mile, the model predicts the travel time to be 2.38 minutes (0.69 + 1.69 = 2.38), or 2 minutes 23 seconds.

A second model, the theoretically derived "square-root law" ([4] Chapters 6,7) was used to estimate the average travel distance (in miles) in a region for the first-arriving company from the equation:

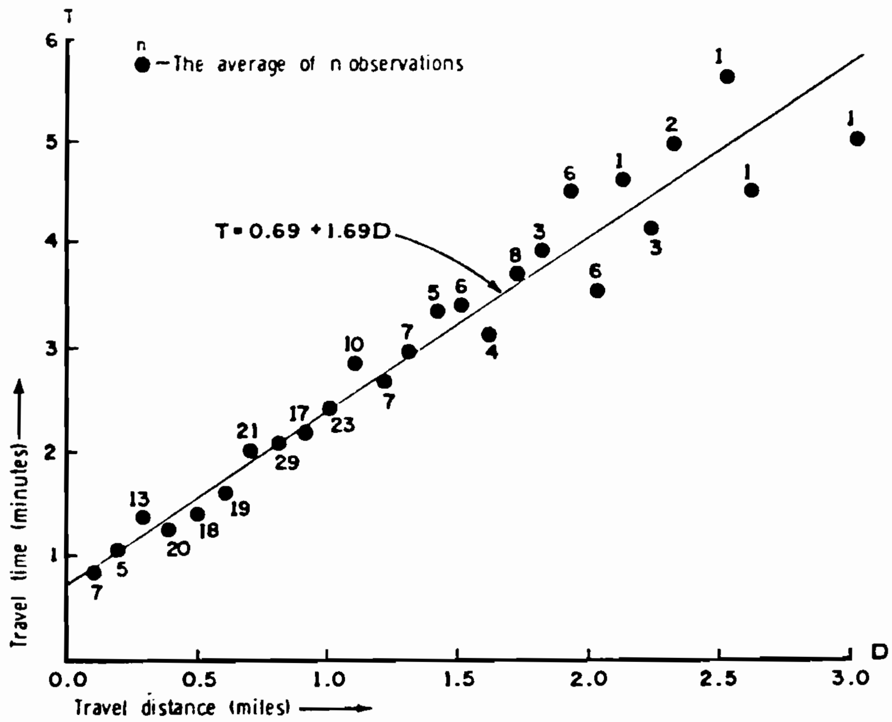

Figure 3.5. The relation between distance and travel time for fire companies in Wilmington, Delaware. Source: Walker, Singleton, and Smith (1975).

$$\bar{D} = \textit{average travel distance} = (\textit{constant})\sqrt{A / \bar{N}}$$

The constant depends on street configuration and on how companies are distributed in the region, A is the area of the region (in square miles), and $\bar{N}$ is the average number of companies available in the region (the average number available is the number located in the region less the average number busy). For cities like Wilmington, a value of 0.55 for the constant was found to give good estimates. Thus the average travel time for the first-arriving engine company in a region in Wilmington with area A and an average of $\bar{N}$ was estimated as

$$\bar{T} = 0.69 + 1.69\ (0.55)\sqrt{A / \bar{N}}$$

It is possible to answer some deployment questions using this simple model. For example, it can be used to determine how the average travel time in a region would change if the number of companies were changed.

A model known as the Parametric Allocation Model [4, pp. 330-348] was also employed in the study. This model was developed to determine fire company allocations that would satisfy a wide range of objectives and to permit them to be evaluated in terms of average regional travel times, average citywide travel times, and company workload. The model incorporates a simple formula that specifies the number of companies that should be allocated to each region, given the total number of companies to be deployed in the city and a parameter that reflects the desired objective.

The formula first makes sure that enough companies are allocated to each region to meet the region's average firefighting workload. The remaining companies are then allocated in proportion to a combination of each region's realized and potential demand. Realized demand is related to the alarm rate in a region. Potential demand is related to the probability that, if an alarm occurs in a region, it will escalate rapidly. A run-down residential area might have a large realized demand because of a high structural alarm rate, but a moderate potential demand because the buildings are all brick. An industrial area, on the other hand, might have a low alarm rate but a high potential demand. The formula incorporates a "tradeoff" parameter that allows the user to determine how much emphasis to place on either type of demand.

The model is constructed in such a way that there are values of the tradeoff parameter giving allocations that satisfy three specific objectives. One parameter value will equalize workloads in all regions; another will minimize the average citywide travel time; and a third will equalize average travel times for all regions.

The user is free to choose one of these three parameter values to obtain an allocation that satisfies one of the three explicit objectives; or he can choose an intermediate value in order to effect a compromise among these objectives. Thus, without specifically embracing a given objective, the manager can generate a variety of allocations and choose the one that he likes best based on his intuition and experience, and on the resulting measures of performance in each region. The model ensures that each allocation is the best one that could be obtained for each compromise.

Since, in this case, the administration was interested in the possibility of phasing out one or more engine companies, the model was used to make a gross determination of what regions in the city should lose companies (if companies were to be eliminated) and how the remaining companies should be allocated.

The question then remained, given a particular number of engine and ladder companies to be deployed in each region, where in the regions should they be located.

To answer this question, a second model, the Firehouse Site Evaluation Model (the "siting model") was used [4, Chapter 10] to evaluate specific locations. Over 100 different fire company arrangements were compared.

The siting model is not an optimization model. It will not specify the "best" arrangement of fire companies. It is a descriptive model. For each configuration that the user suggests, the model will predict the resulting values of a large number of performance measures. A subset of them may be tabulated for comparison with the results from other configurations. The results for several configurations that seem most promising must be evaluated by the policymaker, whose responsibility it is to interpret the numbers in the light of factors that the model does not incorporate--community and union reactions, costs, and other political realities, to name a few. Ultimately, someone who understands the entire operational and political context of the department must decide which of the alternative configurations is the best, all things considered. If none is considered good enough, then still others must be analyzed.

Recommendations of the Project Team. In late 1973, results from the siting model and fire-incidence data on overlapping alarms suggested that the number of engine companies in Wilmington could be reduced by one or two companies and that the remainder could be repositioned with very little effect on fire protection. In particular, the siting model estimated that with eight engine companies (instead of nine) the citywide average first-due engine travel time would increase by 1.2 seconds (1 percent increase). This model also estimated that the average first-due engine travel time to structural fires would increase by 3.6 seconds (2.5 percent). And the maximum first-due engine travel time would not change according to the model.

The project team's proposals for redeployment are shown in Figure 3.6. This map of Wilmington shows the specific moves and the one elimination recommended. The company to be eliminated was Engine Company 7 in Region 1, which shared a firehouse with Ladder Company 3. By eliminating Engine 7, and assigning its stationmate Ladder 3 and the nearby Engine 8 to a new house at location A, two things would be achieved. First, the old house occupied by Engine 7 and Ladder 3 could be closed permanently. Second, Engine 8 would move to a position where it could handle much of Engine 7's former workload.

The project team further recommended that five of the seven remaining engine companies be moved to new houses as they were built at the locations indicated in Figure 3.6. Only one of the two remaining ladder companies, Ladder 2 in Region 4, was to be moved. Ladder 1, and the two engines housed with it, in the new (1971) Center City firehouse were to remain in place.

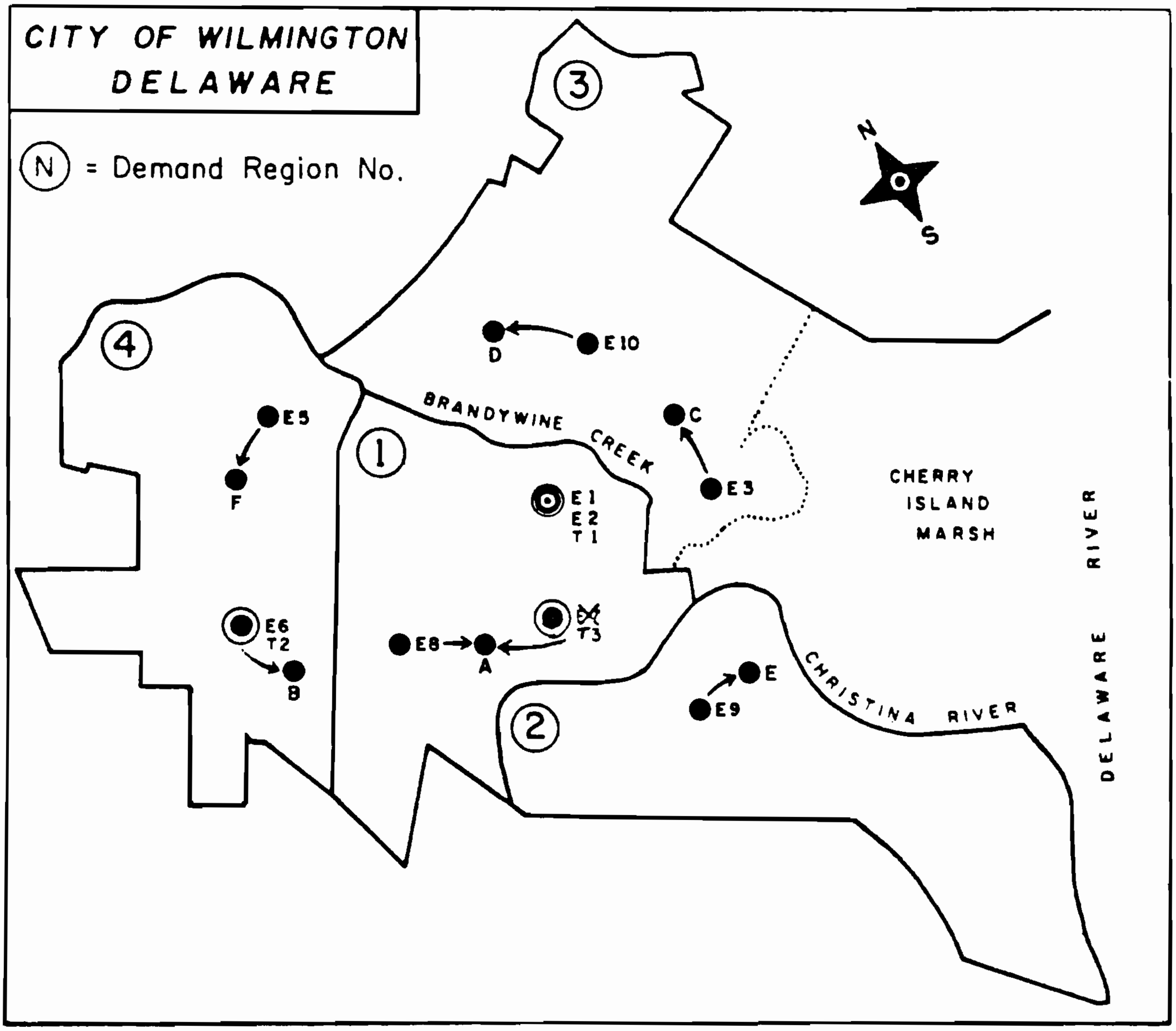

Figure 3.6. The proposed redeployment of fire companies in Wilmington, Delaware. (E = engine company, L = ladder company.) Source: Walker, Singleton, and Smith (1975).

History of the Implementation. The Mayor accepted the recommendations and directed that negotiations with the firefighters' union proceed with the objective of eliminating at least one company. In preparation for the negotiations, numerous meetings of the team and interested city officials were held to identify potential issues and strategies and to gauge union reaction to the proposed cuts. In addition to the cuts, wages and a number of fairly routine issues were to be negotiated.

Negotiations began in April 1974 and continued until a settlement was finally approved by the union membership in October [5]. The city's proposals were offered as a package (a given salary increase, contract language changes, manning cuts, etc.) to be accepted or rejected as a unit. These proposals, including the immediate cut of two engine companies, were presented in detail in the first session. The union responded a few weeks later with a detailed reply opposing any cuts. The city attempted to stimulate movement by proposing a compromise of a one-company cut immediately and one after a 15-month study to examine the effects of cutting the first. This proposal was rejected by the union.

On June 30 the existing contract expired. Although no specific agreement was made, the city continued all of the provisions of the expired contract. However, with no contract, the city had the right to act unilaterally on matters formerly governed by the contract--including the proposed cuts in manpower requirements.

Early in July, the city chose to adopt the position of a "last, best, and final" offer to the fire union. The proposal included a one-company cut. The union negotiating committee agreed to put it to a membership vote, where it was overwhelmingly defeated.

In August, a settlement with the union representatives was reached that called for continued pay parity with police, the elimination of one engine company, and contract language changes. While base pay parity was preserved, the firefighters accepted a $100 annual "uniform maintenance allowance" increase (from $50 to $150) as a type of productivity increase. The contract was submitted to the membership and, once again, was defeated, though by a narrow vote. The reasons for the rejection appear to have been the explicit acceptance of the company cut in the contract and a general feeling that the firefighters had been unduly pressured.

The city response to the negative vote was a strongly worded statement and the unilateral elimination of one engine company (Engine 7) at 8:00 a.m. the following morning. The unilateral action speeded the final settlement by largely removing the issue of cutting one company from the table; it was no longer necessary for the firefighters to agree to it, since it was already done.

Within two weeks the firefighters ratified a new contract, which contained no significant differences from the one previously rejected, other than elimination of the specific agreement to the one-company cut. It has been estimated that the elimination of Engine 7 has saved the city about $240,000 per year, a figure that does not include accrued pension liability.

The elimination of Engine 7 was viewed with alarm by many in Wilmington, especially the firefighters. However, the Commissioner of Public Safety, the Fire Chief, and most firefighters agree that the cut has produced no identifiable reduction in safety either to life or property since it was made. In addition, from January to March 1976 the University of Delaware's College of Urban Affairs studied public perception of municipal service delivery in Wilmington. Fire protection was regarded by those interviewed as one of the best of the city's services. No change relative to the protection prior to the cut was noticed. No one in the city has complained of negative effects since the cut, not even the firefighters' union.

Other progress has been made in implementing the recommendations. In April 1977, Engine 3 moved into a new firehouse built six blocks northwest of its old house and approximately at the location recommended. In May 1977, Engine 8, Ladder 3, and Battalion 2 moved to a new firehouse on the site recommended by the project team. Both of the new houses were dedicated on June 17 with appropriate ceremonies.

An interesting development related to the construction of the two new houses was the creation of standardized plans for building them, resulting in substantial savings in money and time. The other firehouses scheduled to be built in the next few years will be constructed using the same standardized plans. While this is not a direct outcome of the analysis, it is, in the opinion of Wilmington officials, an outgrowth of the team approach and analytical thinking about fire problems.

Wilmington is following the project team's original recommendations in rebuilding and resiting its firehouses, with some minor modifications. Detailed plans for a new firehouse for Engine 9, to be located immediately behind the existing house, are being drafted. Funding for the new house is expected to come from a local public works bill recently enacted by Congress.

The city has also budgeted some of its own capital for firehouse construction. Firehouses for Engine 5 and for Engine 6 and Ladder 2 (one house) will be funded locally. Construction of a new firehouse for Engine 10 would complete the original set of recommendations made by the project team. The reduction in manpower costs from the elimination of one engine company will more than cover the increased debt service engendered by building the new firehouses.

Evaluation. The analytic work performed in Wilmington led to two broad, successful results--the implementation of effective changes in the deployment of firefighting resources, and the creation of an internal ability to perform further analyses as needed. While many influences combined to achieve these results, there are several major themes that can be identified. In short, the experience in Wilmington suggests that these elements were largely responsible for the results:

(1) A well-constituted, well-informed project team, capable of applying analytic thinking and the output of computer models to problem solving.

(2) Timely assistance from outside consultants having experience in using and transferring directly applicable technology.

(3) Skillful labor negotiation, based on both analytic results and a clear understanding of the interests of all parties to the talks.

(4) Support from and decisive action by the chief executive.

Further information on the implementation and evaluation is given in [5,8].

4. PROTECTING AN ESTUARY FROM FLOODING

Background. In 1953, a severe storm flooded much of the Delta region of the Netherlands, killing several thousand people and inundating 130,000 hectares. As a consequence, in 1954, the Dutch government embarked on a massive construction program for flood protection. By 1975, the new dams, dikes, and other works were nearly complete for all Delta estuaries except the largest--the Oosterschelde (Fig. 3.7). There building was interrupted by controversy.

The original plan had been to dam the mouth of the Oosterschelde, completely closing it off from the sea. This threatened the estuary's ecology and its oyster and mussel industries. Opposition developed and the Dutch Cabinet directed the Rijkswaterstaat, the agency responsible for water control and public works, to investigate alternative approaches. In April 1975, this agency set up a joint research project with the Rand Corporation (a California nonprofit) to help with the study. That project, named the *Policy Analysis of the Oosterschelde* (POLANO) is summarized in detail in a series of reports [9, 12, 13, 14, 15, 16, 17]. These publications offer something not usually found in the literature of systems analysis: a detailed report on the approach and results of a study that contributed in an important way to the outcome of a highly controversial public policy decision. The description below is abstracted, with minor changes in wording, from [12], the summary volume of the report prepared for the Rijkswaterstaat (RWS).

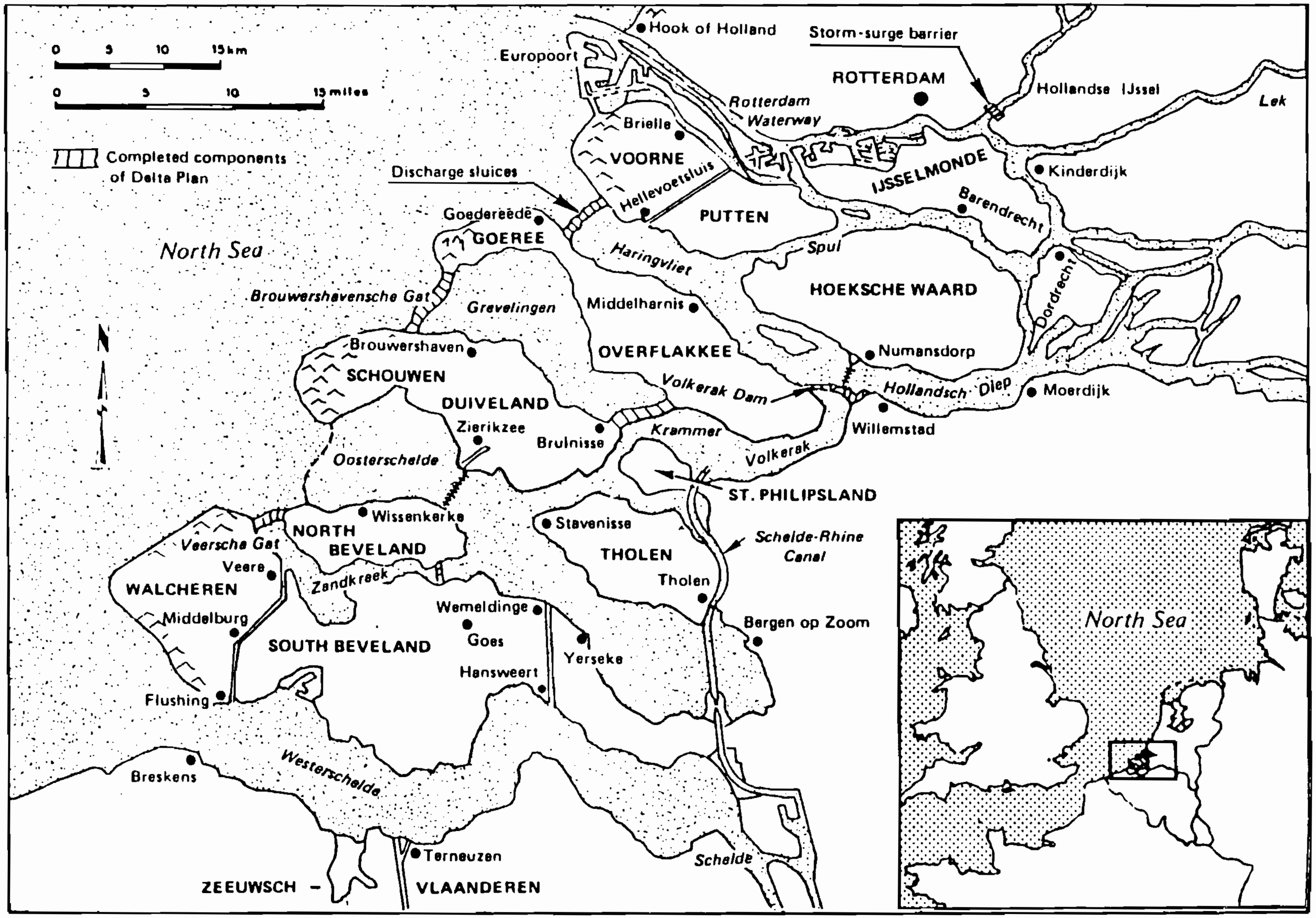

Figure 3.7. The Delta region of the southwest Netherlands, showing the Delta Plan components completed by 1975.

Environmentalists objected that an impermeable dam across the mouth of the estuary, turning it into a fresh water lake, would destroy its rare ecology. They were joined by the oyster and mussel fishing industry. On the other hand, those primarily concerned with safety strongly supported the plan for closing off the estuary from the sea. As an alternative, the Cabinet proposed the construction of a storm-surge barrier in the mouth of the Oosterschelde. Basically, the barrier was to be a flow-through dam with large gates, which would be closed during severe storms. Under normal conditions, the gates would be open to allow a reduced tide to pass into the basin, the size of the tide being governed by the size of the aperture in the barrier. The Cabinet specified that the barrier, to be acceptable, must be completed by 1985 and must provide protection against a storm so severe that it might be expected to occur only once in 4,000 years.

There were still some who feared that the barrier, with its reduced tide, might seriously damage the fishing and the ecology. They pressed for yet another alternative: leaving the mouth of the Oosterschelde open to maintain the original tide and constructing a system of large dikes around the estuary's perimeter to protect the land from floods.

Implicitly rejected at this stage was an obvious fourth alternative of a completely different character: Do nothing at all--or at least almost nothing in terms of the total public expenditures required relative to the costs of the three main alternatives. For example, one version of this alternative might be to:

- Do no rebuilding of the coastal defenses against flooding in the Oosterschelde vicinity (except routine maintenance of the current dikes).

- Limit further action to measures such as enhancing storm prediction capabilities, improving evacuation procedures, and establishing an indemnification fund for compensating future property losses.

In the context of prevailing Dutch public opinion, options of this kind were not a realistic proposition, and, accordingly, were expressly excluded from the scope of the study mandate. Had they been included, the main argument to consider on their behalf would be that the funds currently intended for rebuilding coastal defenses might be more beneficially spent on other needs (e.g., on automobile safety, which also affects both lives and property).

Thus, there were three main strategies to consider for protecting the southwestern Netherlands against North Sea flooding: the closed, the storm-surge barrier, and the open cases. Each involved a number of variations; the size of the aperature in the storm-surge barrier, for instance. The possible consequences of these three approaches (and their variations) on the Oosterschelde environs and the Netherlands as a whole had to be estimated. These consequences, or "impacts" as they were called, are numerous. They include the *security* of people and property from flooding; the *financial costs* to the government from the construction and operation of the works; the changes in the kinds and populations of biological species that constitute the *ecology* of the region; the additional employment and other *economic* effects that occur not only in industries directly involved in building the barrier but also indirectly in other, interrelated industries; the quantity and quality of water available in various locations (called *water management* impacts by the Dutch); and various *social* effects, including the displacement of households and special ramifications on local residents.

A dominant aspect of this type of problem is that most of the consequences cannot be expressed naturally in the same units and some cannot be satisfactorily quantified (e.g., aesthetics) at all. Further, different groups perceive and value particular consequences differently.

In the joint research effort, each organization concentrated on different, but complementary, tasks. Rand's primary task was to develop and apply a methodological framework for predicting and comparing the many possible consequences. The RWS's primary tasks were, on the basis of special engineering and scientific studies, to develop a specific design for each alternative approach, to analyze the consequences of the designs in which it had special expertise (e.g., the effects on salinity) and to provide data, as well as assistance, for the methodology being developed with Rand.

The Analytic Approach. Figure 3.8 portrays the analytic approach, indicating the stages of the analysis.

Screening Alternatives. Each approach for protecting the Oosterschelde has many variations; for example, several different types of storm-surge barriers are possible and several different apertures could be considered for each type. The possible alternatives are so numerous that it becomes impractical to evaluate all of them in terms of detailed impacts. One is thus compelled to identify a manageable number of the most promising alternatives for subsequent evaluation. *Screening* reduces the number of alternatives that merit further evaluation--that is, one identifies the promising alternatives (and rejects the inferior ones). The criteria for screening include security, ecology, and construction costs; for example, an alternative that would not clearly provide the desired level of security or provided it with a higher cost and a less desirable ecology than some other alternative would be ruled out.

The RWS did the final screening, with the help of studies by several special committees and its own investigations.

Designing Cases. Screening identifies promising alternatives to use in designing cases. These *cases* include a scenario (e.g., about the economic future) and a set of technical assumptions. The *technical assumptions* are merely assumed values--explicitly stated--for the most uncertain factors in the system, such as the excess water level associated with a storm having a frequency of 1/4000 or how much wave overtopping will cause dike failure.

Comparing Alternatives and Decisionmaking. For each case the many impacts of the various alternatives are estimated using appropriate models and then presented to the decisionmakers for their comparison of alternatives. The usual presentation combines the different impacts associated with a given alternative into a single measure of performance, but this approach generally loses information and may substitute the analyst's values for those of the decisionmakers. In the Rand approach, the various impacts are displayed on a table, called a *scorecard*, that also shows, by shading, each alternative's ranking for a

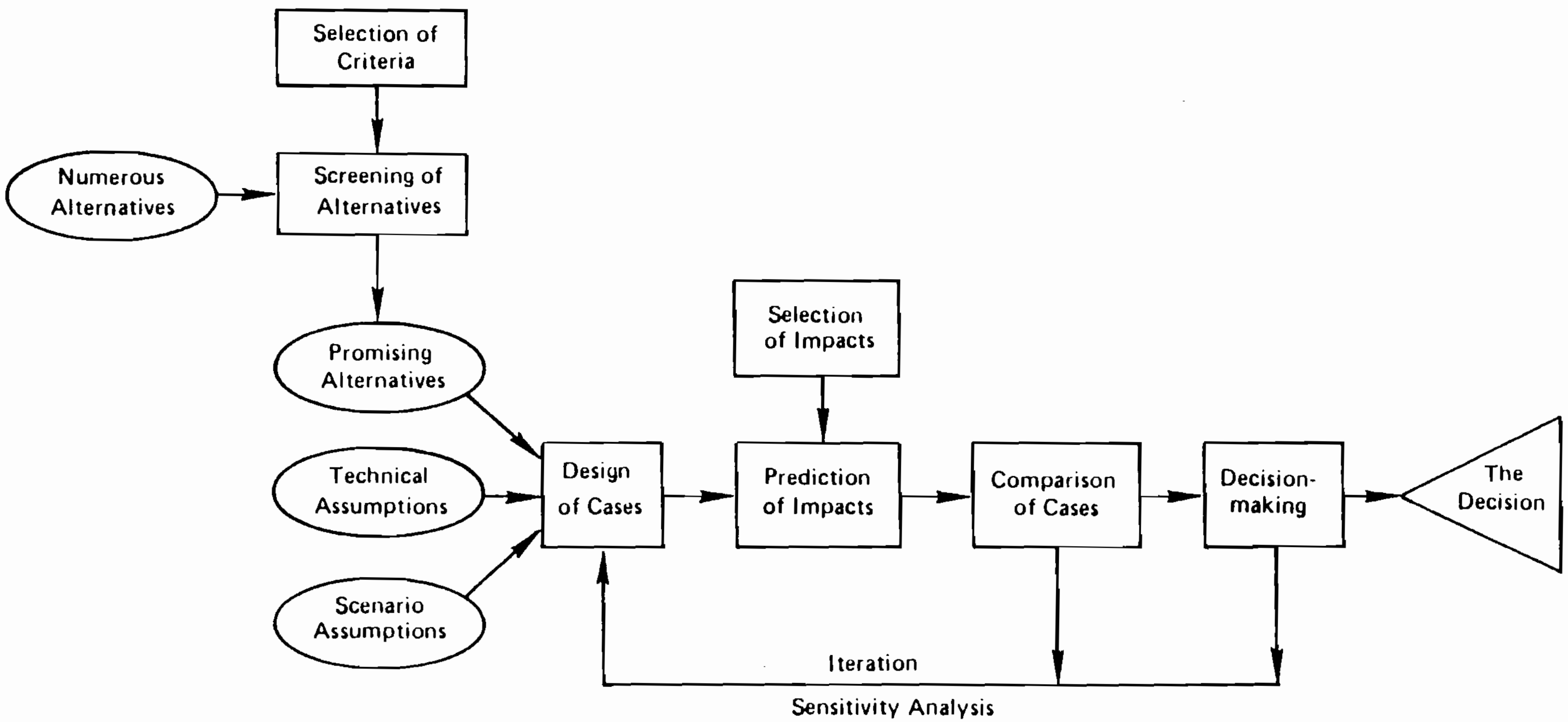

Figure 3.8. The stages of the Osterschelde analysis. Source: [12].

particular impact. To this information the decisionmakers can then add their value judgments about the relative weights to be assigned to the different impacts and cases to thereby select a preferred alternative--that is, to make "the decision." In POLANO, the decisionmakers were considered to be the Dutch Cabinet and Parliament, the elected representatives of the people.

Iterating the Analysis. On the basis of an initial comparison of alternatives, the analysts identified as desirable a number of sensitivity analyses. Additional comparisons were then designed that involved a change in the alternatives, the technical assumptions, the scenario, or combinations of all three. Evaluation of the alternatives in these additional comparisons--or the expressed concerns of the decisionmakers in response--yielded yet another set of changes for investigation. This process continued--iteratively--until the decision was made.

On account of the intensely political nature of the problem, it was recognized that during, and even after, a choice among the three alternative approaches was made, there would be a need to satisfy the desires and allay the fears of the many interested parties. This could not be done by comparing benefit-cost ratios or other single indices associated with the individual alternatives. Instead, environmentalists, fishermen, shippers, vacationers, and so on would want to know as precisely as possible how their area of special interest would be affected by whatever actions were contemplated. These considerations implied two things--the need for very many relatively small models that could answer specific questions, rather than for one or a few large models and for a scheme that would enable not only the primary decisionmakers (the Cabinet) but also the secondary decisionmakers, the Dutch people, to apply their own weights to the impacts they considered significant.

Space limitations preclude describing the many models by which the various impacts were estimated. Many were relatively standard, such as those used by the RWS to estimate dam and dike construction costs, developed through long experience with similar construction projects. Others, such as those used to assess long-run and transient changes in the ecology and in flood security, required developing new methods (with results considerably more uncertain), being handicapped by lack of both experimental data and scientific theory. Nevertheless, rather than omit these components, they were modeled using whatever data were available in combination with the opinions of experts. The decision to proceed reflects a widely held belief, perhaps best stated by Forrester [11]:

> Much of the behavior of systems rests on relationships and interactions that are believed, and probably correctly so, to be important but that for a long time will evade quantitative measure. Unless we take our best estimates of these relationships and include them in a system model, we are in effect saying that they make no difference and can be omitted. It is far more serious to omit a relationship that is believed to be important than to include it at a low level accuracy that fits the plausible range of uncertainty.

If one believes a relation to be important, he acts accordingly and makes the best use he can of the information available.

Methods for Synthesizing and Presenting Results. Once the impacts of the alternatives had been assessed, a major difficulty still remained: synthesizing the numerous and diverse impacts of each alternative and presenting them to the decisionmakers for comparing alternatives. In the usual *aggregate approach* to synthesis, each impact is weighed by its relative importance and combined into some single, commensurate unit such as money, worth, or utility. The decisionmakers use this aggregate measure to compare alternatives. Of the several aggregate techniques, perhaps the best known is cost-benefit analysis, which converts as many impacts as possible to monetary terms and sums the results.[1]

The aggregate approach had several major disadvantages for POLANO. First, the aggregation process loses considerable information: For example, it might suppress the fact that the high costs associated with one alternative are

[1]See Chapter 8 for further discussion.

due to environmental problems whereas those associated with a second alternative are due to financial problems.

Second, any single measure of worth depends strongly on the weights given to the different impacts when they were combined and on the assumptions used to get them into commensurate units. Unfortunately, these crucial weights and assumptions are often implicit or highly speculative. They may impose on the decisionmakers a value scheme bearing little relation to their concerns. For example, cost-benefit analysis implicitly assumes that a dollar's worth of one kind of benefit has the same value as a dollar's worth of another; yet in many public decisions, monetarily equivalent but otherwise dissimilar benefits would be valued differently by different elements in the society. Also, in converting disparate impacts to monetary values, cost-benefit analysis must sometimes make speculative assumptions, such as: How much money is one red-necked grebe worth? Are a million grebes worth a million times one grebe?

Third, the aggregate techniques are intended to help an individual decisionmaker or a close-knit group choose the preferred alternative, the one that best reflects their values (importance weights). Serious theoretical and practical problems arise when, as in POLANO, there are multiple decisionmakers: Whose values get used (the issue of interpersonal comparison of values), and what relative weight does the group give to the preferences of different individuals (the issue of equity)?

It has been proved that there is no rational procedure for combining individual rankings into a group ranking that does not explicitly include interpersonal comparison of preferences [19]. To make this comparison and to address the issue of equity, full consideration of the original impacts appears essential.

Finally, to be theoretically valid, the aggregate techniques (other than cost-benefit analysis) require that the importance (value) of each impact be independent of the size of all other impacts. But in the real world, this condition is not always satisfied. Each impact that violates this condition must be suppressed, either by eliminating it or by treating it at the next level of aggregation.

In POLANO, the analysts chose a disaggregate approach that presents a column of impacts for each alternative, with each impact expressed in natural units. In comparing the alternatives, the decisionmaker could assign whatever weight he deemed appropriate to each impact. Explicit consideration of weighting thus became central to the decision process itself, as we believe it should be. Prior analysis can consider the full range of possible effects, using the most natural description for each effect. Therefore some effects were described in monetary terms and others in physical units; some were assessed with quantitative estimates (e.g., "100 jobs would be created"), others with qualitative comparisons ("recreation opportunities would increase slightly"), and still others with statements of nonordinal facts ("an attractive tourist site would be destroyed"). A disadvantage of this approach is that the amount of detail makes it difficult for the decisionmaker to see patterns or draw conclusions.

To aid the decisionmaker in recognizing patterns and trading off disparate impacts, POLANO applied a useful display device called a *scorecard.* [2] Impact values are summarized (in natural units) in a table, each row representing one impact and each column representing an alternative. The scorecard takes the table of impacts and adds shading to indicate each alternative's *ranking* for a particular impact: White shows the best value, black the worst, and gray the intermediate. An entire column shows all the impacts of a single alternative; an entire row shows each alternative's value for a single impact. Numbers or words appear in each cell of the scorecard to convey whatever is known about the size and direction of the impact in absolute terms--i.e., without comparison between cells. When shading is added to highlight differences in ranking among the alternatives, each impact must be considered separately. (That is, impact values are ranked across columns, for each row independently of all other rows. Shading assignments do *not* involve comparisons between rows.)

---

[2] Scorecards had been used earlier by the project leader, Bruce Goeller, as part of a transportation study conducted by Rand for the U.S. Department of Transportation. For discussion, see Reference [10].

For POLANO, the scorecard had several advantages. It presents a wide range of impacts and permits a decisionmaker to give each one whatever weight he deems appropriate. It helps him to see the comparative strengths and weaknesses of various alternatives, to consider impacts that cannot be expressed in numerical terms, and to change his subjective weighting and note the effect this would have on his final choice. When there are multiple decisionmakers, the scorecard has the additional advantage of not requiring explicit agreement on weights for different social values: It is generally much easier for a group of decisionmakers to determine which alternative they prefer (perhaps for different reasons) than what weights to assign the various impacts.

The ranking assigned (shading) reflects certain assumptions about what is "best" or "worst" for each impact. To derive maximum benefit from scorecards, these assumptions must be made explicit, because different ones (and hence different rankings) might be appropriate in some circumstances and for some interest groups. For example, in times of a slack economy, an increase in employment would be a favorable impact. In that circumstance, the alternative with the largest stimulus to employment would be designated "best" and the one with the least stimulus would be designated "worst." When the economy is straining at full capacity, additional impetus to employment would only result in increased wage and price inflation and would have the opposite ranking.

As this example demonstrates, the assumptions underlying shading assignments can be crucial. Generally, there is little doubt as to which assumptions should be adopted. Sometimes, however, two different sets of assumptions are equally plausible; for example, recreational growth near the Oosterschelde might be encouraged or prohibited. This quandary can be resolved by presenting parallel but separate scorecards for each scenario.

Even apart from the ranking assumptions, scorecards can occasionally impose more of the analyst's value scheme on the findings than appears at first glance. The analyst chooses the impacts to display, their order of presentation, and their units of expression. These choices can, of course, influence the impressions conveyed. To be effective, therefore, scorecards must be carefully designed and interpreted. Other techniques for synthesizing multiple impacts require similar caution but suffer from additional disadvantages, mentioned earlier.

POLANO prepared separate scorecards to summarize each impact category and the entire study. (Examples appear in Tables 3.1, 3.2, 3.3 and 3.4.)

Study Results. The Rand/Rijkswaterstaat POLANO team analyzed and compared many different consequences, called impacts. In addition, a number of sensitivity analyses were performed to learn how the impacts would change with variations in the design of the alternatives and in the assumptions made for several uncertain factors. The most significant impacts--and their major uncertainties--are summarized below.[3]

Costs. In comparing the financial costs for the alternatives, estimated by Rijkswaterstaat engineers, the study concluded that the storm-surge barrier case would require an investment of nearly 4,700 million DFL,[4] a quarter more than the open case and double the closed case. After construction, the annual costs for maintenance and operation would be small, ranging from 10 million DFL for the closed case to 25 million DFL for the storm-surge barrier case. (See Table 3.1.)

Security. To assess the security from flooding, the study developed a method for estimating the likelihood and severity of potential flood damage to land, people, and property under each of the three alternatives. The alternatives were subjected to many simulated threats expressed in terms of storm water levels, and the expected damage from flooding was calculated. The performance of the method and its assumptions were evaluated by comparing its damage estimates with the actual damage values of the 1953 storm.

[3]Except for ecology, the storm-surge barrier impacts are for a barrier with an 11,500-square-meter aperture, the Rijkswaterstaat's nominal design. This aperture would reduce the tide to about two-thirds of its present value.

[4]DFL is the symbol in this study for Dutch guilders, the official monetary unit of the Netherlands. (The FL derives from "florin," the historical unit.) The reader who wants to compare guilders with dollars can use a conversion factor of 2.5 DFL per dollar (40 cents per DFL). This factor was a rough approximation of the fluctuating exchange rate at the time the study was done.

Table 3.1. The financial costs and security scorecards for the Oosterschelde analysis. Source: [12].

FINANCIAL COSTS SCORECARD

(All costs in DFL million)

Item	Alternatives		
	Closed Case	SSB Case	Open Case
Construction cost from Jan. 1, 1976	2135	4645	3620
Annual maintenance and operations	10	25	15
Peak year expenditures	420	690	410
Peak year	1980	1980	1980

Rankings: Best / Intermediate / Worst

SECURITY SCORECARD

Item	Alternatives		
	Closed Case	SSB Case	Open Case
Long run:			
Land flooded (ha) in 1/4000 storm, L(90)[a]	0	0	400
Technical uncertainty	None	Scour	Dikes
Transition period expected damage:			
Land area flooded (ha)	430	200	530
Value of real property flooded (DFL million)	50	20	60
Number of people at risk	800	360	970

Rankings: Best / Intermediate / Worst

[a]For such a storm, there is a 90-percent probability that the amount of land area flooded will be no more than the indicated value.

The degree of safety for each alternative was estimated for two time periods: the transition period, which occurs before the protective construction is complete, and the long run. Although the values of the safety impacts change with the designs and technical assumptions (for example, the water level produced by a once-in-4,000-years storm), it was shown that the safety rankings of the three alternatives remain unchanged for both the long run and the transition period. (See Table 3.1.)

Ecology. For assessing changes in long-run ecological balances, the study developed a method to predict the effects of the different cases on the average abundances of biological species found in the Oosterschelde. This estuary, with its tidal shoals and mud flats, is an ecologically rich natural reserve of international significance. It serves as a feeding area for resident and migratory birds, as a location for the commercial culturing of oysters and mussels, and as a nursery for the young fish and shrimp populations from the North Sea. It was feared that construction associated with the cases would seriously damage this ecology.

The study analyzed the many relevant factors influencing ecology that varied among the alternative cases—different apertures for the storm-surge barrier (which would produce different tides), different sizes for the Western Basin, and different rates for nutrient flows and fishing. For these factors, the method predicted changes in the long-run average abundances of 18 groups of similar species, such as oysters and mussels, fish-eating fish, and plant-eating birds. It considered such natural processes as predation, migration, and photosynthesis. By using mathematical concepts new to ecology and by concentrating on long-run rather than day-to-day changes, the method is considerably easier to apply than traditional models of the same ecosystem. To validate it, its estimates were compared with actual ecological observations made in the Grevelingen, an adjacent estuary recently transformed into a salt-water lake.

The study concluded that the closed case is by far the worst ecologically and that one's preference among the other alternatives depends on one's goal for ecology. If the goal is to minimize the change from the present ecology, in terms of total amount of biological life (biomass) and relative species abundance, the preference will be the open case or a storm-surge barrier case with a large aperture (20,000 square meters). But if the goal is solely to maximize total biomass,[5] one should prefer a storm-surge barrier case with an aperture between 6,500 and 11,500 square meters. However, the preference should not be firm, because of uncertainties concerning the amount of nutrients imported from the North Sea in the storm-surge barrier case.[6] Thus, although ecological considerations may help one to reject the closed case, they do not strongly distinguish between the open case and the storm-surge barrier case in which the aperture exceeds 6,500 square meters. (See the ecology scorecard, Table 3.2.) The choice among these alternatives will thus depend strongly on other factors, such as cost and security.

Beside the long-run changes discussed above, the study considered three transient disturbances to the Oosterschelde ecology. First, after construction, there would be a "rapid kill" of biomass where the reduced tide dries out the organisms or where the water becomes fresh. For this transient effect, the closed case, with the largest tidal reduction, is by far the worst. The open and storm-surge barrier cases have roughly one-third the kill, with the open case best by a small amount.

The second transient ecological disturbance considered was the possibility that oxygen-free (anaerobic) water will be created in the Eastern Basin of the Oosterschelde when it is converted from a salt-water to a fresh-water lake. This conversion would kill the existing flora and fauna, and their subsequent decomposition by bacteria might temporarily deplete the oxygen in the newly freshened water. The further decomposition of the dead organisms, occurring while the water remained oxygen-free, would produce bad odors and murky

[5]And if one is willing to accept the consequent shift of relative species abundance from the present situation in favor of noncommercial bottom species such as snails and worms.

[6]This nutrient import is in the form of dead organic matter (detritus). Rand recommended that the detritus import be measured directly. When this was done, the figure obtained, 870 tons per day, turned out to be remarkably close to the 700 tons per day predicted by the model (Table 3.2), which, because it greatly exceeded the import rate predicted by others, had been the subject of controversy.

Table 3.2. The ecology scorecard for the Oosterschelde analysis. Source: [12].

Item	Alternatives: Closed Case	Alternatives: SSB Case	Alternatives: Open Case	Present Oosterschelde
Key inputs:				
Salt basin area (sq km)	202	365	370	476
Tidal range at Zierikzee (m)	0	2	3	3
Primary production (tons/day)	200	350	350	450
Detritus import (tons/day)	0	990	550	700
Percent of present primary food available[a]	17	116	78	100
Total biomass:				
Amount (tons afdw[b])	5200	29700	21300	28500
Percent of present amount	18	104	75	100
Potential abundance of birds:				
Benthos-eaters (tons afdw)	1	9	7	10
Fish-eaters (tons afdw)	4	.06	.03	.05
Plant-eaters (tons afdw)	More	Same	Same	
Potential shellfish culture:				
Mussels (percent of present)	13	90	100	100
Oysters (percent of present)	0	90	100	100
Nursery function:				
Shrimp (percent of present)	0	400	50	100
Fish (percent of present)	0	133	73	100
Transients:				
Rapid kill of benthic biomass (tons afdw)	11500	4500	4200	
Rapid kill (percent of present benthic biomass)	68	27	25	
Change in average density of benthic biomass from present (g/sq m)	-25	22	-1	
Number of years to stabilize	6.5	6	0	

Rankings: ☐ Best ▨ Intermediate ■ Worst

[a]Primary food available = primary production rate + detritus import rate.

[b]Ash-free dry weight.

water, and prevent the growth of almost all organisms suited to a fresh-water environment.

The study concluded that anaerobic conditions were not likely to occur in the Eastern Basin if a small fresh-water lake were created, regardless of its month of closure, although sustained below-average wind velocities could cause transient anaerobic conditions if this basin were to be desalinated in the summer. Anaerobic conditions are likely to be encountered if a large fresh-water lake is created and closed off during the months of June through September. (It is precisely these months when closure would probably take place, because calm weather is considered essential for the final stages in constructing the compartment dams.) By this criterion, alternatives that involve a small Eastern Basin were favored. (Anaerobic conditions appeared quite unlikely in the Northern Basin.)

The third transient ecological disturbance considered was algae blooms--population explosions in these organisms. When conditions are favorable to algae, as a consequence of construction activities in the Oosterschelde, the resulting bloom may poison the fish and plants, clog filters in water systems, or discolor the water. Or, when conditions become unfavorable, the bloom may suddenly die off and the bacterial mineralization of the dead algae may then deplete the water of oxygen, which can cause the death of desirable fish.

The study developed a method to estimate the risk of algae blooms in salt water. Although there is little likelihood of basinwide fish-killing algae blooms in the unchanged Oosterschelde or in the Western Basin for any of the alternatives, local problem spots may occur on very sunny days in places with stagnant water and abundant nutrients from agricultural runoff or waste discharges. The study reached no conclusions about algae blooms in the Eastern Basin because there were insufficient data about nutrient concentrations and insufficient time to extend the methodology to fresh water. It recommended research to remedy this, noting that algae blooms, unlike the other transient disturbances considered, could be a recurring threat, aggravated by future growth in regional activities.

Economic and social impacts. The study examined the three alternatives in light of their effects on jobs and profits in the fishing industry; changes in recreational opportunities and demand; savings to the carriers and customers of the canal shipping industry; total (direct plus indirect) changes in production, jobs, and imports for the 35 industrial sectors of the national economy; and, finally, as social impacts, the displacement of households and activities and the disproportionate effects on the regional economy.

Even before the study began, there had been extensive speculation in the Netherlands on dire economic and social consequences of construction in the Oosterschelde; the potential shutdown of the local fishing industry, for example, was a major concern. A main conclusion of this study is that most of the economic and social effects would be minor--and some even beneficial. The gains in total employment from the construction and the losses in the fishing industry are possible exceptions. (See Table 3.3.)

Recreational impacts. Under the then current Dutch policy, endorsed by regional and national agencies, the Oosterschelde and most of the central Delta area was to be kept in as undeveloped a state as possible. Because this policy might change, the study examined the recreational impacts under two contrasting policy scenarios. The first assumed that the present policy of no investment in recreation would be retained; the second that an unrestrained investment policy would be adopted. The predicted impacts under the two policies are shown in Table 3.4. Note that in reading this table, the "best" designations for the no-investment case are assigned to the alternative that would do most to minimize recreational activity in the Oosterschilde vicinity. For the unrestrained-investment case, however, "best" is linked to maximizing benefits to recreational visitors.

Table 3.3

Commercial fishing scorecard

Annual Fishing Losses	Alternatives: Closed Case	SSB Case	Open Case
Jobs	199	7	0
Production (DFL million)	30.3	1.4	0
Value added (DFL million)	13.7	10.6	0
Export revenue (DFL million)	<2	<1	0
Domestic consumption (DFL million)	<1	<1	0

Rankings: Best / Intermediate / Worst

Inland shipping scorecard

Impact Measures	Alternatives: Closed Case	SSB Case	Open Case
Cost savings to industries that ship goods (1976-1999, DFL million, undiscounted)	27.2	8.9	0
Separation of commercial and recreational traffic	Much	Some	Little
Are alternate routes always available?	No	Yes	Yes

Rankings: Best / Intermediate / Worst

National economy scorecard

(Total[a] increases in peak year)

Item	Alternatives: Closed Case	SSB Case	Open Case
Jobs	5800	9000	5700
Imports (DFL million)	110	200	130
Percent stone imports	2	4.8	5
Production (DFL million)	580	940	560
Wages and profits (DFL million)	250	400	230

Rankings: Best / Intermediate / Worst

[a] Direct plus indirect increase.

Regional effects scorecard

Item	Alternatives: Closed Case	SSB Case	Open Case
Number of households displaced	0	0	124
Total (direct plus indirect) economic:[a]			
Production (DFL million)	-37	13	38
Jobs	-230	90	290
Road travel:			
Improvements in opportunities	Medium	Minor	Slight
Damage to rural environment	Medium	Minor	Slight

Rankings: Best / Intermediate / Worst

[a] Increases, peak year.

Table 3.4. The recreational impact scorecard for the Oosterschelde analysis. Source: [12].

Type of Recreation	No Investment Case			Unrestrained Investment Case		
	Closed Case	SSB Case	Open Case	Closed Case	SSB Case	Open Case
Sea beaches:						
Added shoreline (km)	8	[0]	[0]	[8]	0	0
Increase in attendance (annual visits, in thousands)	338	[0]	[0]	[>338]	0	0
Inland beaches:						
Added shoreline (km)	17	(11)	[6]	[17]	(11)	6
Increase in attendance (annual visits, in thousands)	108	(88)	[68]	[>108]	(>88)	>68
Boating:						
Sea access restricted for large boats?	Yes	Yes	[No]	Yes	Yes	[No]
Added moorings due to departure of						
Fishing vessels	<160	[0]	[0]	[<240]	0	0
Large boats	<900	<900	[0]	[<900]	[<900]	0
Sportfishing:						
Decrease in salt-water fish quantity (percent)	75	[0]	(25)	<75	[0]	(25)
Added shoreline (km)	17+	(11+)	[6+]	[17+]	(11+)	6+
Fresh-water fish available?	[Yes]	No	No	[Yes]	No	No
Touring:						
Decrease in attractiveness of areas around dikes	[None]	(Minor)	Major	[None]	(Minor)	Some
A major tourist site at mouth of Oosterschelde?	[No]	Yes	[No]	No	[Yes]	No

Rankings: [17] Best; (17) Intermediate; 17 Worst

Conclusions. Unlike many analyses, POLANO did not conclude by recommending a particular alternative. Rather, it compared the alternatives in terms of their many different impacts, but left the choice to the political process, where the responsibility properly resides. POLANO contributed in a direct and substantial way to this process by clarifying the issues, assessing the consequences, showing the influence of uncertainty, and comparing the alternatives--as comprehensively as possible--in a common framework.

Table 3.5 presents the summary scorecard for the nominal cases. It displays most, but not all, of the impacts considered. Some were omitted to make the comparison manageable; these were generally small enough to seem politically unimportant, or were comparable in size for all cases, or were highly correlated with other impacts already displayed.

Certain general observations can be made. First, there was no dominant alternative—one that was best for all the impacts. Second, each case had a major disadvantage that might be considered sufficiently serious as to render the alternative unacceptable to the decisionmakers: The storm-surge barrier case was by far the worst for cost; the closed case for ecology; and the open case for security.

Third, the alternatives differed in the size of their change from the then present situation; the closed case offering the most extreme changes, desirable and undesirable, for most impacts (cost being a notable exception), and the open case offering the least change (except for the displacement of houses); the SSB case was usually intermediate, although it had the largest values for total biomass, the national economy, and financial cost.

Finally, the alternatives show their primary advantages and disadvantages in different impact *categories*. The closed case was by far the best for cost, near best for overall security, but very much the worst for ecology and fishing. The SSB case was best for security (assuming the scour problem is solved) and employment, near best overall (depending on the goal) for ecology, but by far the worst for cost. The open case was perhaps best for ecology overall

Table 3.5. The summary scorecard for the nominal cases for the Oosterschelde analysis. Source: [12].

Item	Alternatives: Closed Case	Alternatives: SSB Case	Alternatives: Open Case	Present Oosterschelde
Financial Costs (DFL million)				
Construction cost from Jan. 1, 1976	2135	[illegible]	3620	
Annual maintenance and operations	10	25	25	
Peak year expenditures	420	690	410	
Security				
Long run:				
Land flooded (ha) in 1/4000 storm, L(90)[a]	0	0	400	
Technical uncertainty	None	Scour	Dikes	
Transition period expected damage:				
Land flooded (ha)	[illegible]	200	530	
Value of real property flooded (DFL million)	50	20	60	
Number of people at risk	800	360	970	
Ecology				
Transients:				
Rapid kill of benthic biomass (tons afdw[b])	11500	4500	4200	None
Gradual loss of biomass (tons afdw)	[illegible]	-8000	[illegible]	None
Long run:				
Time to stabilize (years)	[illegible]	6.0	0.0	
Total biomass (tons afdw)	[illegible]	29700	[illegible]	28500
Potential benthos-eating birds (tons afdw)	[illegible]	9	7	10
Potential fish-eating birds (tons afdw)	4	[illegible]	.03	.05
Potential mussels (percent of present)	13	[illegible]	100	100
Potential oysters (percent of present)	0	[illegible]	100	100
Fish nursery function (percent of present)	0	133	[illegible]	100
Fishing				
Jobs lost	199	[illegible]	0	
Annual production loss (DFL million)	[illegible]	[illegible]	0	
Accumulated net loss (DFL million)	89	0	0	
Shipping				
Accumulated savings through 1999 (DFL million)	27.2	[illegible]	0	
Recreation				
No-investment policy:				
Added sea beach visits[c]	[illegible]	0	0	
Added inland beach visits[c]	[illegible]	[illegible]	68	
Percent decrease in salt-water fish quantity	5	0	[illegible]	
Number of moorings added	+1060	+900	0	
National Economy (Peak Year)				
Jobs[d]	[illegible]	9000	5700	
Imports[d] (DFL million)	110	200	[illegible]	
Production[d] (DFL million)	[illegible]	940	560	
Regional Effects				
Number of households displaced	0	0	124	
Jobs,[d] peak year	-230	90	290	
Production,[d] peak year (DFL million)	-37	13	38	

Rankings: (white box) Best (shaded box) Intermediate (black box) Worst

[a] For such a storm, there is a 90-percent probability that the amount of land area flooded will be no more than the indicated value.

[b] Ash-free dry weight.

[c] Annually, in thousands.

[d] Total (direct plus indirect) increase.

(depending on the goal), best for fishing, but worst for employment and certainly security.

As in all such studies, the impacts and conclusions presented in this report must be viewed with certain qualifications. First, strictly speaking, these results apply only for specific designs or for the variations on those designs considered in the sensitivity analyses. This qualification is important primarily for the SSB, whose design is still in flux; indeed, the SSB design has recently been changed from pillars-on-pits to a new concept called the *pillar solution*. Most of the conclusions, however, are quite robust: A design modification may change the *value* of a particular impact, but usually not its *ranking* with respect to the other alternatives. For example, a new design for the SSB is likely to have a different cost than the pillars-on-pits design, but the SSB case will doubtless still be the most expensive and create the most employment.

Second, there are several major uncertainties underlying the results; these could alter the values for particular impacts and, in some instances, their rankings. There is one major uncertainty common to all cases: the future recreational policy in the Oosterschelde region; if it were to switch from the present no-investment policy, intended to discourage recreational growth, to an unrestrained-investment policy, then the recreational impact values shown in Table 3.4 would be changed and all the rankings would be reversed. Except for this, the closed case has no major uncertainties, and the open case has only one--the risk of structural defects in the dike foundations, whose potential size and possible solutions are both unknown. The SSB case, however, has several major uncertainties in addition: Its construction costs may be underestimated because it is a large-scale R&D project; it needs additional research on the scour process to ensure that the risk of serious scour is in fact negligible; and it needs measurements of detritus import and sedimentation to reduce the ecological uncertainties.

The decision. On April 5, 1976, one year after POLANO began, Rand presented a summary report in the form of an all-day briefing at the Rijkswaterstaat Headquarters; this briefing described the methodological framework that had been developed and summarized the results of the POLANO analysis. Rand then helped the Dutch members of the POLANO team combine the jointly obtained POLANO results with the results of several special Rijkswaterstaat studies. This work became the foundation of the Rijkswaterstaat's May 1976 report, *Analysis of Oosterschelde Alternatives* [*18*], which was presented first to the Cabinet and then to Parliament, along with the Cabinet's recommendation for a decision.

The Cabinet recommended the storm-surge barrier plan, with a small Eastern Basin, to Parliament. This plan was adopted in June 1976, but no aperture size was specified for the barrier. Parliament requested additional analysis by the Rijkswaterstaat to help determine the best aperture size, in the range from 11,500 to 20,000 sq m. In September 1977, on the recommendation of an interdepartmental advisory committee, Parliament approved an aperture of 14,500 sq m. Construction is now under way.

Even before construction of the storm surge barrier began, it was realized that more detailed attention had to be given to the control strategy for operating its many large gates. Such a strategy includes 1) the actions that govern the time and rate of gate closing and opening, 2) the rules behind the decisions for these actions, and 3) gathering and processing the required information. The strategy had implications that would affect the design of the barrier. To assist the Rijkswaterstaat in determining a control strategy, a Barrier Control (BARCON) Project was established in April 1977. The Rijkswaterstaat contracted with Rand for the study and set up a Dutch counterpart research team to help. The study has been completed and is reported in [9].

5. PROVIDING ENERGY FOR THE FUTURE

Today's economies run largely on fossil fuels--coal, natural gas, and especially oil--energy sources that in the next forty, fifty, or one hundred years will be exhausted or at least too costly to exploit except for very specialized purposes. To provide the necessary energy, these economies must soon begin to use renewable sources and do so at an expanding rate. Whether this rate can be accelerated rapidly enough not to require radical changes in growth and consumption patterns throughout the world is a question that presents a host of problems, technical, social, and political.

In mid-1973, during the so-called "energy crisis," IIASA began a program of study to provide insights into the long-term dimensions of various energy problems. It was clear--or at least it soon became clear--that the term energy crisis was misleading; the difficulties associated with supplying and using energy were not temporary and were spread throughout society. They would continue and the nations of the world would have to learn to deal with them. The objective of the study became more focused: to find a feasible way to provide sources of energy that could be sustained for the foreseeable future. The aim was not to find the optimal way or even a politically acceptable way, but merely, given a few reasonable assumptions about political and social conditions, to find a technologically possible path to get us from the state of uncertainty about energy that existed in the 1970's and still exists today to a state in which future energy sources appear secure and adequate for the entire world. The study is reported in a two-volume work entitled *Energy in a Finite World* [20], from which this report is abstracted.

A fifty-year time frame from 1980 to 2030 was selected for the study. One reason for the need to consider such a long time period is that, in the past, it has taken roughly fifty years for a new type of primary energy to increase its market share from 10 to 50 percent of the total supply. It was also felt that at least two human generations or fifty years would be needed to accommodate changes in the social infrastructure that must parallel the required changes in the technical infrastructure. For certain aspects of the study fifty years is not long enough, particularly when one looks ahead to the inevitable time when there really are no fossil resources available.

Also it became clear that no long-term solution to the energy problem could be achieved entirely within a single nation or region. One reason is that the impact of energy-related human activities on the environment can no longer be considered negligible. Another is that today roughly 25 percent of the world's energy comes from one place on the globe, the Middle East, and this creates a strong technical and political linkage to almost all parts of the world. On the demand side the situation is similar. It thus seems appropriate to treat the world as a whole, for otherwise more than one nation may plan to import the same barrel of oil, ton of coal, or uranium ore.

Many factors impact on every path to an energy future. These include the current demand for energy and the changing rate of increase of this demand, the absolute size of energy resources and the allocation of these resources through trade, the build-up rates of supply facilities, the rate at which new sources can be introduced, the total size and nature of the environmental and ecological impacts, the management of these impacts, the societal and political acceptance of the required technical and economic changes, the relation between energy policy and social problems, and possibly others. A complete investigation would require that all these elements be handled adequately. On three of these, although they were considered in the study--innovation rates, management of environmental and ecological impacts, and social and political acceptance of technoeconomic changes--the IIASA team felt that more complete research than they could provide was needed. The last factor, the relation between energy problems and policies and more general social problems, was not treated, although a number of relevant assumptions were made. One, constraints on possible solutions were limited to those that were physical or structural; political and social constraints were recognized but were not applied explicitly, allowing the entire range of technologically possible alternatives to be explored. Two, the study assumed a surprise-free future; no major catastrophes such as nuclear wars and no technological breakthroughs of a nature that cannot be anticipated today were assumed to occur. Three, population and economic growth were assumed to be modest (a world population of no more than 8×10^9 by 2030, for instance). Also assumed were major energy conservation and aggressive exploration for additional energy resources plus a functioning world trade in oil, gas, and coal so that the interim needs of all the various parts of the world could be met. Four, in all cost evaluations, the dollar and other monetary units were assumed to have constant value, thus decoupling the terms of trade from the effects of inflation.

The project started by characterizing energy demands, supply opportunities, and constraints and matching them up. To manage the wide variety of resources, economic systems, and industrial structures found in the various nations and regions of the world, it was found possible to consider seven groupings homogeneous in the factors of interest. These regions were selected for their economic and energy similarities rather than for geographic proximity. The study did not merely add up national energy projections but examined regional economic growth patterns and energy intensity trends that, when coupled with population figures and prices, provided long-term estimates of energy demand.

Demand. Three major factors change energy demand--population, economic, and technological growth. The demand is also affected by the associated changes in lifestyle and urbanization. To estimate these changes, a breakdown even finer than into regions was required. As derived by the IIASA studies, the expected number of people on earth was estimated to increase from 4 billion (10^9) to 8 billion by 2030. As illustrated in Fig. 3.9, the flattening of the population growth curve would have largely taken place by 2030, making it possible to envisage population conditions as becoming relatively stable. Total primary energy demand was estimated to lie somewhere in the range of 16 to 40 TWyr/yr (1 terawatt-year, or 1 TWyr, is 10^{12} watt-years, and

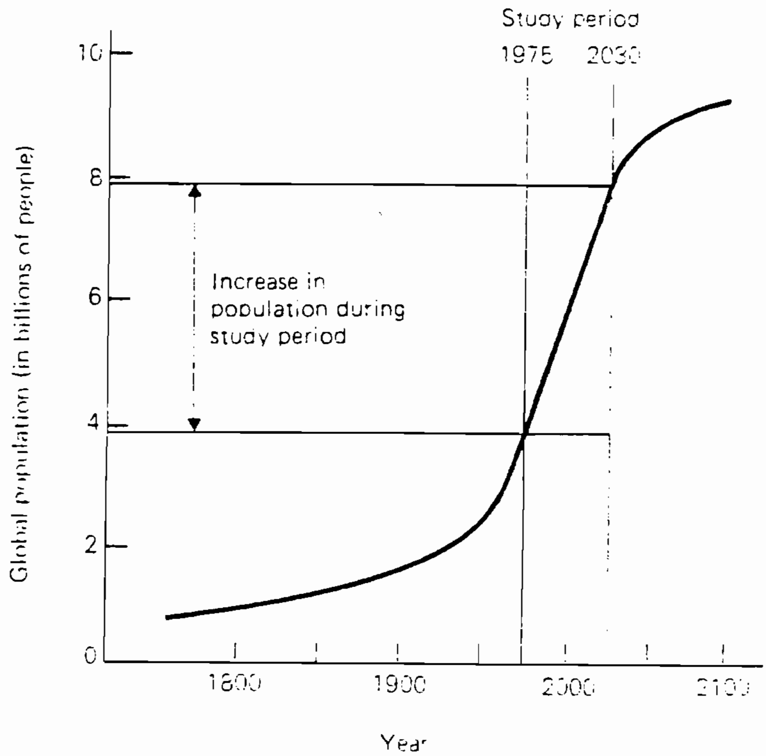

Figure 3.9. The estimate of the world's population growth used in the IIASA energy study. Source: Energy Systems Program Group [20].

is equivalent to 5.2×10^9 barrels of oil). In 1975 global primary energy consumption was 8.2 TWyr/yr.

One other important factor in the demand for energy is the real cost of energy--that is, its cost relative to other goods and services. The use or nonuse of energy cannot be considered a principal goal; energy is an input to lives and work, along with other resources. Depending on the costs, one exchanges the amounts of the various inputs to produce the results one wants. When the price of energy goes up, we use less of energy and more of other things.

Technological progress tends to increase efficiency and thus to decrease energy demand. Changes in lifestyle can either increase or decrease energy demand. Up to now the result has been a decrease in demand per unit of productive output but an increase in per capita energy demand, an increase that is expected to continue.

Another factor affecting energy demand is urbanization; increased urbanization brings with it an increased per capita consumption of energy. By 2030 it is expected that 70 percent of the world population will live in urban areas as compared to slightly over 40 percent today.

Supply. The study established that, in a purely physical sense, there is no energy supply problem. There are sources whose production rate and durability are virtually unlimited; this is true, for instance, for nuclear breeders and fusion reactors and for solar power. The world has just not as yet invested the capital and prepared the facilities to make use of these sources. With additional large investments of capital and skill, the study demonstrated that environmental and ecological impacts can almost totally be eliminated. Strong conservation measures will largely take care of demand. Hence, in a technical sense, given adequate time to take the necessary measures, there should be no energy problem. But there is one and it is getting worse. The problem thus becomes one of finding a path to doing what is necessary that is not only possible in principle but also one that humanity may be persuaded to take.

Such a path is beset by constraints--on water, land, materials, manpower, risk, market substitutability, and so on. Supply capabilities are constrained by whatever forces limit each particular technology--public approval for nuclear power, carbon dioxide for fossil fuel combustion, market penetration and the economics of central station supply for solar power. Each potential source -- nuclear, central station solar power, individual small-scale solar installations, wind, biomass, ocean currents, and so on--had to be investigated in depth and its advantages and drawbacks taken in account.

Consider coal, as an illustration. The total amount of recoverable coal that might fall within reach of economically viable technical capabilities is tremendous. But to exploit it there are very large water, energy, land, material, and manpower requirements coupled with the problem of building the mining and transportation capabilities for producing and handling it. Burning it in the quantities required to substitute for oil and gas would violate any limit one might like to set on carbon dioxide emissions.

Consequently, one must look at coal in a way different from the way coal has been used in the past. It cannot be the dominant energy source in a high energy-consuming world. But, as a large resource of chemically reduced carbon, it can be used as a base from which to synthesize liquid fuels when oils become too expensive--as they must eventually. For the demand for liquid fuel is the driving force behind the energy problem. The study therefore devoted most of the coal work to ways to convert the coal enterprise, stepwise, into a liquid fuel synthesis industry, and to do it in a way that would minimize carbon dioxide emissions. This implies allothermal liquefaction by using hydrogen produced exogenously from nuclear or solar sources along with carbon from coal to produce methanol or other synthetic hydrocarbons. This method, as opposed to autothermal liquefaction in which the process heat comes from coal itself, requires less coal and releases far less carbon dioxide.

System properties. The energy problem exists in the context of the continuity of human institutions and the maintenance of a healthy environment. This context acts as an overall constraint on what can be done to eliminate the energy problem.

Demands, resources, technologies, and constraints must be integrated and balanced in order to find out if a feasible path to a sustainable energy future can be established. In the study, this integrating and balancing was worked out iteratively by developing two scenarios plus a number of variations. The first, the IIASA high scenario, was chosen to be consistent with relatively high economic growth throughout the world, leading to a level of global primary energy consumption in 2030 equal to slightly more than four times the 1975 level. The other, the IIASA Low scenario, assumed lower economic growth rates, leading in 2030 to a little less than three times the 1975 rate of primary energy consumption. Table 3.6 shows the energy demand developed from the two scenarios, and Figure 3.10 shows the proportionate shares (the coal liquification growth being especially important).

The preparation of these scenarios and of the variations was done by the use of a sequence of mathematical models, assisted by the judgment and intuition (i.e., by the various mental models) of the participants. Neither of these scenarios is a prediction of what future energy development might be like; the future might develop like either of the two scenarios but the possibility it would do so is extremely unlikely, although it might well fall somewhere in between, say in the total energy consumed by 2030; it might do so, however, but still differ widely in how the sources were distributed between, say, nuclear and solar power.

The supply explorations and the scenario constructions are, in a sense, the tangible products of the study; the first demonstrates that the required energy is physically present and the second indicates plausible and consistent ways in which new energy sources might first supplement and then by 2030 essentially replace the current fossil sources.

Table 3.6. Global primary energy demand by source for the high and low scenarios. (The figures in the table are in terawatt-years per year, TWyr/yr, one terawatt being 10^{12} watts, and one TWyr being the equivalent of $5.2x10^9$ barrels of oil.)

Primary source	Base year 1975	High scenario 2000	High scenario 2030	Low scenario 2000	Low scenario 2030
Oil	3.83	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar	0	0.10	0.49	0.09	0.30
Other[a]	0	0.22	0.81	0.17	0.52
Total[b]	8.21	16.84	35.65	13.59	22.39

[a]Includes biogas, geothermal, and commercial wood use.

[b]Columns may not sum to totals owing to rounding.

Source: Energy Systems Program Group [20].

(a)

(b)

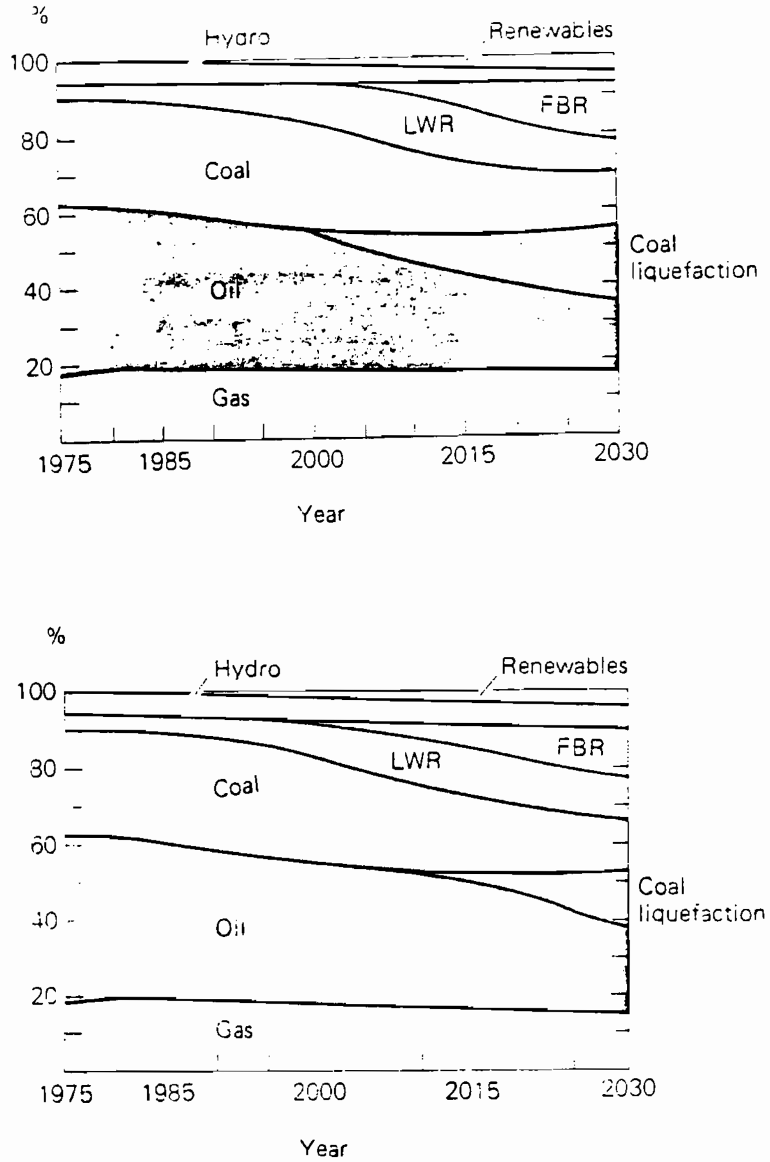

Figure 3.10. The global primary energy shares by source for (a) the high scenario, and (b) the low scenario. Source: Energy Systems Program Group [20].

The most important conclusion of the study is that it is technically feasible to meet the world's future energy needs. There are, of course, difficulties and expenses involved. But the world is not doomed to failure because nature has not given us the necessary endowments for 8 billion people, or even for a larger number, such as 10 or 12 billion. There is thus a factual basis or platform on which political issues, such as setting environmental standards or determining development policies for nuclear power, can be settled.

REFERENCES

Improving blood availability and utilization

1. Brodheim, E. and G. Prastacos (1979) "The Long Island Blood Distribution System as a Prototype for Regional Blood Management", *Interfaces* 9(5), pp. 3-20.

2. Prastacos, G. (1980) "Blood-Management Systems: A Overview of Theory and Practice" IIASA, Laxenburg, Austria, PP-80-1.

3. Prastacos, G. and Brodheim (1980) "PBDS: A Decision Support System for Regional Blood Management" *Management Science*, 26(5), pp. 451-463.

Improving fire protection

4. Rand Fire Project (1979) (Warren E. Walker, Jan M. Chaiken, Edward J. Ignall, eds). *Fire Department Deployment Analysis* North Holland, New York.

5. Singleton, David W. (1975). "Firefighting Productivity in Wilmington: A Case History" *Public Productivity Review* 1 (2), pp. 19-29.

6. Walker, Warren E. (1975). "The Deployment of Emergency Services: A guide to Selected Methods and Models", R-1867-HUD, The Rand Corporation, Santa Monica, California.

7. Walker, Warren E. (1978). "Changing Fire Company Locations: Five Implementation Case Studies" (023-000-00456-9) Government Printing Office, Washington DC.

8. Walker, Warren E., David W. Singleton, and Bruce Smith (1975). "An Analysis of the Deployment of Fire-Fighting Resources in Wilmington, Deleware" R-1566/5-HUD, The Rand Corporation, Santa Monica, California.

Protecting an estuary from flooding

9. Catlett L., et al. (1979) "Controlling the Oosterschelde Storm-Surge Barrier--A Policy Analysis of Alternative Strategies" Vol. I, Summary Report R-2444/1-NETH, The Rand Corporation, Santa Monica, California.

10. Chester, L. G. and B. F Goeller (1973), "The STAR Methodology for Short-Haul Transportation: Transportation Impact Assessment" R-1359-DOT, Sec. II, The Rand Corporation, Santa Monica, California.

11. Forrester, J. W. (1969), *Urban Dynamics*, Massachusetts Institute of Technology Press, Cambridge, Mass.

12. Goeller B. F. et al. (1977), *Protecting an Estuary from Floods— A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California (RR-2121/1-Neth); Vol I *Summary Report* (A. F. Abrahamse, J. H. Bigelow, R. J. Gladstone, J. C. Bolton, D. M. DeFerranti, J. C. DeHaven)

13. ______(1977), *Protecting an Estuary from Floods— A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California: Vol II *Assessment of Security from Flooding* (A. F. Abrahmse, J. H. Bigelow, R. J. Gladstone, B. F. Goeller, T. F. Kirkwood, and R. L. Petruschell).

14. ______(1977), *Protecting an Estuary from Floods—A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California (RR-2121/1-Neth); Vol III *Assessment of Long- Run Ecological Balances* (J. H. Bigelow, J.

G. Bolton, J. C. DeHaven).

15. _______ (1977), *Protecting an Estuary from Floods— A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California (RR-2121/1-Neth); Vol IV *Assessment of Algae Blooms, A Potential Ecological Disturbance* (J. H. Bigelow, J. G. Bolten, J. C. DeHaven)

16. _______(1977), *Protecting an Estuary from Floods—A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California (RR-2121/1-Neth); Vol V *Anaerobic Conditions and Related Ecological Disturbances* (J. H. Bigelow J. C. DeHaven).

17. _______(1977), *Protecting an Estuary from Floods—A Policy Analysis of the Oosterschelde* The Rand Corporation Santa Monica, California (RR-2121/1-Neth); Vol VI *Selected Social and Economic Aspects* (F. J. P. Heuer, and J. W. Weehuizen).

18. Rijkswaterstaat, (1976). "Analysis of Oosterschelde Alternatives" An English translation is also available: Policy Analysis of Eastern Scheldt Alternatives, Nota DDRF-77.158, The Hague, May.

19. Sen, A. K. (1970) *Collective Choice and Social Welfare* Holden-Day, Inc., San Francisco.

Providing energy for the future

20. Energy Systems Program Group of IIASA, Wolf Haefele, Program Leader (1981) *Energy in a finite World: Volume 1. Paths to a Sustainable Future; Volume 2. A Global systems analysis*. Cambridge, Massachusetts: Ballinger Publishing Company. See also *Energy in a Finite World: Executive Summary*. Laxenburg, Austria: International Institute for Applied Systems Analysis.