Community Values and Operations Research

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If there is any characteristic that can be singled out as the distinctive phenomenon of our twentieth century it must be the rapid growth in the complexity of organizations and their decision processes. Errors in making decisions can be extremely costly in both human and material resources. Indeed, the long life of many capital investments means that the results of some errors may be, for all intents and purposes, irreversible.

Certainly the decision problems involved in urban transportation and land-use planning are among the most difficult and complicated decisions we can make. We face the question, "What will be the impact of a certain transportation system on the way of life in a community?" Even to define what is meant by the phrases "transportation system" and "community" is extremely difficult. How do we establish limits on such a question? How do we choose between those factors we wish to consider and those we feel irrelevant? How do we validate or even test our assumptions about what is relevant and what is not?

Community opposition to transportation plans has made it obvious to the transportation planners that "transportation" is no longer a well-defined field of interest. The construction of the Interstate Highway System through our countryside is not an adequate prototype for the construction of freeways and mass transit lines through our cities and suburbs. In the urban setting, the transportation planner faces problems of land use, relocation of housing and business establishments, recreation planning, economic development, and the proper integration of the area immediately affected with those contiguous to it. He must consider the differences between long, short, and intermediate term effects of his planning decisions. All of these considerations and many others must be considered as a package, rather than as distinct and more or less unrelated elements of the plan.

The need for establishing sound and systematic decision processes that can handle a large number of variables often interrelated in intricate ways gave rise to operations research, which applied the methods of the physical and mathematical sciences—and more recently, of the social sciences—to the solution of organizational decision problems. To deal successfully with a decision problem, it must be formulated or modeled. Next, the model must be solved in such a way that the decision is optimized against some set of objectives, and third, the solution must be implemented and controlled. Let us start by considering problem formulation.

VALUES IN DECISION PROBLEMS

Values enter directly into the process of problem formulation. As the decision process is modeled, the value structure of the organization is directly reflected in the model itself, where it is explicitly observable. Effective operations research (OR) requires that the OR study team include the participation of individuals within the organization, since the primary task of the team and of the sponsoring organization is to insure that values are correctly embedded in the model. This raises the interesting question of whose values should be incorporated in the objective function used in the model. In community studies it is community values that should be used, but what is the community? How are divergent elements in the community represented by the objective function? Is the OR team's approximation of community values sufficient or should the "decision-maker's" value structure be used? Indeed, the most difficult aspect of most decision problems is the construction of the objective function that is to be optimized.

Given the nature of the decision, various courses of action are developed that represent alternative ways of dealing with the problem at hand. The inventiveness and the creativeness of the OR team and the sponsoring organization are the only real limit to the form and extent of the alternatives. Indeed, the development of alternative courses of action can be one of the most valuable and innovative facets of the use of operations research. It is in this phase of the project that policy content is developed (1).

Specifically, the function to be optimized must contain a set of measurable objectives and a set of weights that scale the individual objectives by relative importance. The mathematical form of the function aggregates the weighted individual objectives into a single number, which measures the contribution to the relative effectiveness of each of the objectives. The criterion function can be constrained to insure that the individual objectives represented in the function take on values that lie within some acceptable range. It is through the objective function that community values enter into the operations research models, as each of the alternatives is appraised by evaluating it in terms of the objective function.

The exact way in which each value is included in the decision model depends on the way in which that value is defined and on its measurability (2). The various elements of a community value system are not generally revealed overtly unless someone violates or threatens to violate the values held by the community. Clearly, it is revealed values that we must measure and include in our models. We must remember that the strength of these values will vary over time, and that their strength is usually inversely related to the degree to which the community feels that the value is threatened (3). We must remember that these revealed values are unique to the specific time and place, the specific communities involved, and the specific public investment program under consideration. While there may be basic similarities of response to transportation plans made in different communities, the exact nature and strength of the response must be viewed as an ad hoc phenomenon. If a set of values is fairly well defined, measurable, and independent, the values may be aggregated by simple addition, properly weighted, of course. Many, if not most, of the models concerned with public investments are of this type, include cost-benefit models and most of the transportation-land value models that incorporate econometric methods for determination of weighting factors or coefficients.

For example, Wingo's model of transportation cost (4) and, for that matter, most of the other similar models, including the works of Alonso and Haig (5, 6), take a set of undefined community values and develop from them a set of economic costs. Values enter such models indirectly as elements that describe cost as a function of distance, time, or frequency of trips between the center of the city and various points away from the center.

All of this sounds quite straightforward, but one is reminded of Artemus Ward's remark, "It ain't the things we don't know that hurts us, it's the things we do know that ain't so." Models that focus solely on cost contain within them the assumption that the relationships between costs and community values do, in fact, behave as the arithmetic of the model implies. Second, there is the implied assumption that other things are either invariant or similarly affected as the variables of the model take on different values, Either or both of these assumptions may be in error. For instance, Deroudille's work casts considerable doubt on the seemingly obvious notion that residential land values decrease as the time and distance between the land and the center of the city increases (7). Quite possibly, the usual hypothesis about time-distance-cost is true, but there are other factors that more than offset the distance-cost factor. Other problems in the application of cost-benefit models are discussed by Lichfield (8).

The distance-cost relationship has the strong advantage of being more or less directly measurable. It can, therefore, be made an element of the objective function. It would be most convenient if all of the elements we wished to include in the objective function could be expressed in a common dimension—and not uncommonly we attempt to force such a happy state by assigning dollar values to everything. We now know, however, that our objective function should contain several elements with very different dimensions—for example, measures of use of a facility, disturbances or distortions in community living and/or travel patterns, changes in the tax base, the number of business establishments forced to relocate, changes in the balance of political power, direct and indirect employment effects, measures of congestion, and the level of racial and ethnic integration, to mention only a few.

Since the units in which these variables may be measured are quite different, they cannot be simply aggregated. The numbers, however, can be considered as indices of the level of the variable as well as direct measures of it. If we arbitrarily take the indices as dimensionless, and develop a set of weights such that each variable has a weight that represents its importance relative to the other elements in the function, we can now aggregate across the variables. The output of the function will be dimensionless and will represent a relative measure of effectiveness for the system being described. The components of the objective function will be blended together, each receiving its appropriate weight and contributing to the output in accordance with its importance.

There are two general methods for deriving these weights—the "revealed preferences" method suggested by Samuelson (9), and various direct measurements of subjective judgments, employing such techniques as pair-wise comparisons, the Delphi method and others (10, 11, 12, 13, 14). These methods have been successfully used in a number of diverse cases and the act of quantification insures that the weights receive conscious attention (15). Through these weights, the values of the community are employed directly to influence the output of the objective function. It is critical to remember that the weights must be considered dynamic. As community values change, the weights must change so that planning for a future time period can reflect the dynamism of the community.

At times it is not particularly desirable to enter relevant variables directly into the objective function. For example, planners may specify some minimum level of traffic speed or wish to hold congestion below some critical level. In such cases the variable can enter the model in the form of a constraint on the choice of alternatives.

Even in cases where the variable to be included is not so obviously measurable as congestion or speed, it may be included either in the function or as a constraint. Freeway designs, for example, can be differentiated by their aesthetic qualities as well as their routes or engineering. Given a basic design, beauty is partially related to cost. Within limits, the more funds we devote to landscaping, the more pleasing the resultant project is apt to be. If this relationship can be estimated by the planners or by a "fine arts committee" it can be used in the objective function. If the committee is unable to develop the relationship, but can detect three or four different levels of beauty, the project can then be constrained to meet some minimum level of aesthetic acceptability. Above all, important objectives must never be excluded simply because they are difficult to measure. Of what real worth is an analysis when the analyst (16) writes:

> The ugliness of the elevated highways that cut indiscriminantly across cities, the dislocations caused to families whose property is taken for highways, the smog from the increased number of vehicles encouraged to use the highway, and the increased congestion in the central cities...are certainly all additional costs arising from the construction of the Interstate System; however, there is no way to measure or to quantify them. Consequently they must be ignored....

The analyst is suspicious of subjective data and so he seeks varables with dollar-cost or time dimensions because they are directly measurable and seem to be objective. Often they are not nearly so objective as they appear. Time spent in congested traffic patterns at a freeway exit probably does not have the same impact on an individual as an equal number of minutes spent waiting for stoplights on city streets or walking to and from his parked vehicle. There is no particular need or virtue in aggregating all variables in the objective function that happen to have the same dimension. They may have quite different weights or may be subject to different constraints. In such cases, it is helpful to maintain strict separation of such variables.

The process of building the objective function is never truly complete. As the analysis of various plans is undertaken, new factors will occur to the analysts that should be included in the evaluation since they will be seen to contribute to or detract from the worth of the proposed public investment in the community system. In practice, the limits of the analysis are set by common sense. If variables have an impact so weak that they cannot appreciably affect the outcome or decision, they should be excluded. Further, even though a given variable may have a high level of impact on the outcome, it may not be appreciably variant with the alternatives being considered, and can be excluded. In any case, the objective function is always a partial measure of the value or cost of an alternative since it is neither feasible nor possible to describe any complex real-world system completely.

Once the objective function is constructed, each alternative is evaluated and the best alternative can be selected as the recommended decision. Clearly, the outcomes of the evaluation process are highly dependent on the environment that impinges on each of the alternatives. The environment, therefore, is a description of those things that will affect the value of an alternative but are not under the control of the decision-maker. A given transportation plan will produce different outcomes depending on such uncontrollables as the design of future vehicles, the general growth and development of the area to which the plan is applied, area population growth, and other similar environmental factors.

Since the nature of the future environment is usually not known with certainty, a set of the reasonably probable environments should be developed and each of the alternatives evaluated for each of the states of nature. The results can then be arrayed as a "payoff matrix", which is simply a table of all outcomes. The Delphi method and other techniques for quantifying subjective information can be used to estimate the probability that any of the environments postulated will pertain in the future. With these probabilities, the "expected value" of any of the alternatives can be determined and the "best" alternative selected.

Let us digress for a moment to consider what is really meant by the phase "best alternative". Since we are considering a system that can be only partially described at best, and since it contains a number of elements that are quantifications of subjectively determined information, and since the objective function contains a number of elements that are certainly probabilistic in nature, and are not apt to be nicely behaved mathematically, it is impossible to speak of an optimal solution in the mathematical sense. We seek system improvement through better solutions and more insight into the real nature of the problems we face. We are not at this time able to seek the "best" solution and "perfect" insight into our problems.

The approach to the selection of a transportation plan we are suggesting is through the use of statistical decision theory. It is based on an analysis of the relevant system and is used to compare the expected values and uncertainties involved in serveral alternative solutions to a single transportation problem. The measures developed are relative, not absolute, and so we cannot compare the value of a transportation system with the value of extended social services or exploration of the moon. The courses of action evaluated must be alternative means of achieving the same ends.

Given this basic description of the nature of how values are incorporated in operations research models, let us turn to a consideration of several specific types of models to investigate briefly the uses to which they may be put, their strengths and limitations, and some of the key assumptions underlying them.

OPERATIONS RESEARCH METHODS

Mathematical programming is a class of methods for use in solving resource allocation problems. This method is particularly useful in evaluating the effectiveness of alternative transportation plans in meeting community objectives for different costs of system designs.

In linear programming, we are concerned with optimizing a linear (or proportionate) function of the resources available to several activities, subject to linear constraints expressed in these resource variables. In this method we assume that community values are additive or linear in the resource categories. Accordingly, although linear programming has received a considerable amount of research in developing and refining techniques for finding solutions, these methods are typically useful in community value problems only as initial approximations.

Nonlinear programming methods have not been completely successful in providing solutions to community value optimization problems in closed form. That is, we are not able to apply available mathematical recipes, which will find optimal solutions to these problems, except in a few special cases. Nevertheless, nearly optimal answers to nonlinear problems can be developed through successive approximations, although the determination of the proper functional forms and estimations of parameter values remain very difficult. Whenever approximations are obtained, sensitivity simulations can be applied that test the effect of errors on solutions and alternative policies.

Dynamic programming has proved to be a very useful technique in those cases where it may be applied. This method is used when the problem can be decomposed into a set of sequential decisions. In general, this method evaluates the consequences of a large set of sequential outcomes and enables us to select the sequence of decisions that provides the optimal final outcome, where any final outcome depends on the decisions and outcomes that preceded it. Time need not be involved in dynamic programming problems, and the method may be useful whenever optimization is required across two or more independent dimensions. For example, in the budget allocation problem undertaken to implement a freeway plan, a dynamic programming formulation was used to allocate resources to reduce the opposition of political pressure groups (14).

Stochastic programming is a useful technique for optimizing certain objective functions where the parameters or constraints are given in probability terms. Generally, closed-form solutions using this method can only be obtained in very special cases of the objective function, but heuristic techniques will find nearly optimal solutions.

Integer programming is a helpful method for selecting projects or systems to best achieve a specified performance criteria. The most useful situation is where the choice variables can take on only a small number of integral values. Particularly in the case of large problems, the selection or evaluation of projects can be solved using this method.

Finally, decomposition methods in large-scale mathematical programming applications are being developed that extend the range of solutions to system design problems. It is necessary to say, however, that the ability of operations research to formulate problems of this type is much greater than our ability to arrive at mathematically optimal solutions. At the same time, it should be emphasized that heuristic methods will give us very good answers—approximately optimal answers that are often far better than those generated by conventional approaches and rules of thumb.

Computer simulation is the most widely used method for testing out alternative proposals for solving transportation problems. Characteristically, we develop a series of mathematical models representing the subsystems of a complex transportation system, using estimates of parameter values. Computer programs are prepared that incorporate the models and simulated data on how the system would perform under varying conditions of demand and use. The results are predictions of the distributions of system characteristics under a variety of conditions.

Some examples of computer simulation are the following:

1. Case performed a simulation study of the Northeast Corridor rail transportation system to determine the number of vehicles and operating schedules for specified demand and levels of service (17). Considerable skill is required to model and program the characteristics of this system.
2. Airport terminal and airline operations have been simulated to find the effect of varying sizes of aircraft on passenger movement and handling. Although individual elements of the system may be modeled, including passenger ticketing, baggage handling, and aircraft arrivals, no comprehensive overall systems model exists (18).
3. Traffic light operations may be simulated, where some initial results may be obtained by applying priority and multi-channel queuing theory (19).
4. Highway traffic may be modeled using differential equations and the physical theory of follower phenomena (20). Systems results for a city may be obtained through the use of a large-scale computer simulation.

Computer simulation is also a powerful tool when applied to problems involving the estimation of costs, values, and weights discussed. Not uncommonly, the transportation planner is faced with the difficult task of developing "trade-offs" among objectives that are conflicting—for example, the objectives of "mobility" and "stability" put forth by Ylvisaker (21). Simulations using different weights for these objectives will quickly expose the implications of various "exchange rates".

Operational gaming is useful in modeling a city's transportation management problems. Recent developments of an urban management game show promise of exploring alternative solutions in simulated real-life situations using people as participants in the exercise. This form of gaming has proved to be very beneficial in both industrial and military areas of application (12).

PROBLEMS AND SOLUTIONS

In modeling community systems, approximations are required so that complex problems may be studied. Usually, a mathematical model is generated that yields a tentative solution as well as an indication of the effect of missing factors on the solution. An iterative procedure is usually performed where, in succeeding stages of the research study, additional factors are incorporated in the models.

The tools of sensitivity analysis are also quite useful in handling complex problems. Sensitivity analysis provides a method of determining what should and what should not be included in the models. Basically, we simply make changes in the parameters one by one and check to see how the output of the model responds to these changes. Not uncommonly, it is found that very large changes in some parameters can be made before the output is appreciably changed. This indicates that the variable or parameter in question need not be carefully controlled, and we can devote our attention to more important matters.

It is also sometimes useful to see just how sensitive our solution is to slight changes in the mathematical form of the model. Clearly, we would perfer to work with arithmetically simple models if we do not distort the problem in our search for computational simplicity. Testing various formulations can often lead to important simplifications, which will increase our capacity to generate answers to variations in the input data.

A major problem affecting the use of community values in projects is the implementation of plans and programs. Usually, it is impossible to simulate full-scale operations in the planning process. Furthermore, in many cases, implementation occurs long after the original plans were prepared and circumstances may mitigate against their adoption. Successful systems studies incorporate the implementation problems in the research phase. In addition, research specialists and organizational behavioral scientists may be assigned the task of investigating alternative designs for implementation, including the formation of community groups to aid in implementation. The development of plans for the Chicago Crosstown Expressway and the Watts section of the Century Freeway in Los Angeles are both excellent examples of such planning.

In one study of a freeway system, the implementation issue was posed as a problem in the reduction of opposition to the freeway. Using the method of "side payments" referred to by Altshuler (1) and others, the cost of reducing this opposition by various means was estimated, as was the political power of various opposition groups. (To some extent, the measurement of the political power of the interest groups was, in fact, a measurement of the "degree of participation" to which Altshuler also refers.) Estimates were made of the probability that each of the ways taken to reduce the opposition would be successful, and a mathematical programming solution was generated that minimized the cost of implementing the freeway with a given probability—that is, reducing opposition below some critical level (14).

It is interesting to note that public opposition to a freeway may be interpreted as a statement that, as far as the opposing groups are concerned, the perceived costs are greater than the perceived benefits. Although this does not fix the level of either cost or benefit, the ability to implement a plan implies that the perceived benefits are equal to or greater than the perceived costs for the political groups that play an active role in the decision process.

Since the transportation systems are rarely implemented all at once, it follows that transportation plans must be highly responsive to changes in the technical, social, and economic environment.

Adaptive planning is a method for successively modifying initial plans in the light of changing operations and reviews over time. Successful long-range plans require the consideration of possible future environments and values. One specific configuration to the future may seem probable when the transportation system is developed, and the plan will assume that certain extensions of the system will be undertaken at later dates. But the best-laid plans of transportation experts have much in common with the plans of mice and men, so alternate futures must be considered and the problems of transition from one to the other must be a part of the original plan (23). When the basic Interstate Highway System was planned, we did not foresee the rise of militant black power, for example, but as the highway system is extended into urban areas black power is an important element of the environment and the system design cannot ignore it.

Finally, considerable attention must be given to the basic economics of many of our public systems. For example, in many congested urban areas, it is quite clear that the total cost to the community for a vehicle containing only a driver is significantly greater than the price paid by the vehicle's driver. One recent suggestion would be to charge a toll at bridges and tunnels inversely related to the number of passengers carried. It should be noted that this proposal is contrary to the accepted procedure for charging for such services.

CONCLUSIONS

The coupling of community values and mathematical models seems, on the surface, to be a strange and inappropriate marriage. It is not. If anything, this wedding was made in heaven. The problems of transportation planning are so large and complex that mathematical models are rapidly becoming an absolute requirement for rational planning and decision-making. The brute fact that such models are imperfect partial descriptions of the plan and the system to which they are applied does not mitigate the necessity for their use. The fact that our ability to quantify the shadowy stuff of community values is limited to approximations does not mean that we can ignore our ultimate constituency. The fact that operations research gives no guarantee of ideal solutions should not deter our search for better answers to the critical questions we must face. The fact that mathematics cannot solve all problems, including many of those that can be quantified with relative ease, does not imply that mathematics is useless as a tool for planning.

Operations research cannot solve complex transportation problems. The necessity for planners and the public, working in concert, to make difficult decisions will not disappear simply because we employ mathematics. Operations research will merely help to systematize our information and our decision processes. Living as we do in an ad hoc world, change is the only permanent element. We must introduce order into our consideration of this changing world, with its changing needs and changing values.

Probably the greatest utility to emerge from the application of operations research methods to problems involving community values is the insight gained by working at the problems. The construction of an operations research model is a creative act, as is the development of the alternative courses of action that are to be evaluated. The process of doing operations research almost invariably generates a higher level of understanding of the system under study and of the elements affecting the system. Last, but certainly not least, the process of modeling introduces a sense of logic or order into our attempts to understand, control, and coordinate complex, dynamic systems.

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