ROLE OF SYSTEMS ANALYSIS IN TRANSPORTATION CURRICULA

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This paper suggests some guidelines on how systems analysis should be used in transportation and on which techniques should be developed for what research. Six hypotheses are presented, and the implications of these hypotheses for curriculum development are discussed and related to current experience at M.I.T. The paper defines the multidisciplinary approach to systems analysis, and the difficulties involved in establishing a multidisciplinary effort in problem solving are pointed out.

•THE SYSTEMS APPROACH and the many techniques associated with it are increasingly being integrated into the planning and design of public facilities. Yet their role in transportation is not clear. Worse, there is actually considerable question on how systems analysis should be used in transportation systems planning. Faculty members in transportation quite legitimately wonder which of these new tools they ought to select for emphasis and how they ought to integrate this field into their curriculum.

An already substantial and increasing number of professionals in practice, government, and universities believe that the systems approach has a significant role in the planning, design, and operation of transportation facilities and networks. The number of firms using these approaches, the extent of governmental support, and the range of universities either offering or planning courses or programs in transportation systems are strong evidence of the endorsement of the systems approach.

In a general way, the systems approach implies a comprehensive attack on the problems of designing and operating complete sets of facilities. The current emphasis on this overall planning is almost certainly to some extent a reaction to an earlier focus, almost exclusively on detailed analyses of particular projects. But, and most importantly from our point of view, this trend is reinforced and accelerated by our rapidly expanding technical capacity for dealing with an accuracy and rapidity previously impossible with large-scale problems.

At present, the concept of the systems approach is specifically and inextricably attached to the new planning process and design procedures made possible by the computer. Indeed, the development of this technology has engendered an extensive catalog of powerful computer-based techniques. These permit the consideration, explicitly and analytically, of more alternative designs and of more concepts for operation than ever before. The opportunities offered by these new analytic methods have appeared very great.

Consequently, industry, government, and universities have each devoted considerable effort to the development of capabilities in transportation systems analysis. Substantial computer facilities and large computer-based models are in evidence throughout the transportation planning field. No "respectable" regional or urban transportation plan is complete without substantial expenditures for the accumulation of extensive files of data and for their manipulation with one of the many variants of planning models. FHWA urban transportation programs are a typical example of what has been done so far.

All these investments of time and resources might, mistakenly, lead one to believe that there is a high level of confidence in the validity of the new methods of analysis now associated with the systems approach. Actually, however, there are simply not many examples of particular cases in which systems analysis and the systems techniques have been applied with especially beneficial results to real-world problems in transportation planning and design. Many of the applications have been failures, and the majority of these have probably generated fairly trivial results at great expense. Only very few good examples of the use of systems analysis in transportation are available (3).

Although one would hope for a substantial body of evidence justifying the confidence and the resources dedicated to transportation systems analysis, it is not yet available. Such evidence is needed to justify (or refute) confidence for the directions that have been taken. Secondly, this evidence, these lessons of practical experience, should also help us define more precisely what these directions should be.

One of the important intellectual questions before the profession is, What is the role of systems analysis in transportation? I propose that we address this question as we should any research proposition, by formulating and testing specific hypotheses. Experience would indicate that this is really necessary to accumulate firm knowledge, and it certainly would be desirable to know how we should employ systems analysis before we devote substantial further efforts to it and in particular before universities expend the great effort needed to establish new curricula.

The basic issue before us can be stated in terms of three specific questions:

1. To what classes of transportation problems can the various techniques of systems analysis be applied profitably?
2. Which of the many techniques available are appropriate to particular problems?
3. Which techniques deserve emphasis in practice and in a transportation systems curriculum, which should be deemphasized, and what new ones are needed?

It is important for all transportation planners to be able to answer these questions accurately so that time and effort are not wasted. It is quite likely and is often suggested by practicing professionals that systems approaches are frequently applied where they may not be especially useful or to improperly formulated problems. We should learn to avoid this. Likewise, a clearer understanding of what specific approaches are really useful would do a great deal to rationalize the wide variety of subjects that are now offered in transportation systems curricula throughout the country. More insight into the strengths and weaknesses of alternative approaches would, finally, also permit the universities to form more capable and resourceful planners and designers.

CURRENT STATUS

Before an appropriate curriculum in transportation systems analysis is formulated and discussed, it is useful to understand what people perceive systems analysis to be and how they are using it. To establish this, the M.I.T. Civil Engineering Systems Laboratory undertook a national assessment of the status of systems approaches in civil engineering in 1971-72. This review consisted of two parts: a direct questionnaire and a consideration of past surveys of activities and published discussions.

Practicing professionals in both industry and universities were polled to determine how they felt about systems analysis. Faculty members were identified first by compiling a list of those who were known to be using either of two recent texts on systems analysis or engineering (1, 4). Secondly, prospective faculty respondents were identified through catalogs and lists of universities offering degrees in systems analysis and transportation systems in particular. Similarly, a broad range of practicing professionals was identified from a listing of U. S. consulting firms, which contained brief descriptions of their interests.

The evidence obtained from the questionnaires was supplemented by the results of surveys of Vidale (13) and Johnson (8). In addition, the articles by Eldin (6), Gross (7), Kavanagh (9), Tabak (12), and Wagner (14) were consulted. The overall results are presented below.

The Concept of Systems Analysis

In general, there was remarkably widespread agreement that the systems approach is a comprehensive attack on problems, which applies appropriate technological knowledge and economic and other theory, in a rational and systematic manner, to generate optimal plans and designs. The analysis itself is to be done by using whatever tools are appropriate but, at present, particularly by exploiting the new computer-based methods.

It is also widely believed that the skills and knowledge needed to carry out transportation systems planning and design are not, now, to be found in any one academic department or discipline but must be taken from several. This suggests the need for multidisciplinary activities that, somehow, transcend individual disciplines.

The overall agreement on the general definition of systems analysis does not imply a common understanding of how the methodology can or should be used to attack real transportation problems. Quite the contrary is actually true. There is, apparently, little specific agreement on the strengths, weaknesses, and relevance of the particular techniques or approaches available. Although it is, logically speaking, possible for this disagreement to arise because there might really be little to choose from among the techniques, such does not seem to be the case. Individual experience appears to indicate, again and again, that many particular approaches are, in fact, much more applicable to certain classes of problems than to others. It therefore appears reasonable to conclude that the evident disagreement about which methods should be used arises because we have not yet, as a profession, thought through this question clearly.

Optimization Versus Modeling, Evaluation, and Implementation

If we were to predict the future from the published evidence in transportation literature and journals, we would be forced to conclude that transportation planners are nearly universally agreed that optimization methods are at the core of transportation systems analysis. Yet this is not the case.

Our questionnaires and the surveys of others suggest that respondents feel that as much emphasis needs to be placed on modeling and evaluation as on specific forms of optimization. Prime areas of concern are the causal modeling of individual and collective behavior, as represented by demand functions and the evaluation of transportation projects in light of the multiple objectives of the different communities affected by any set of projects. Further, the actual practice of transportation planning indicates that far more attention is paid to various forms of simulation, such as traffic assignment, than to any form of optimization. Johnson's survey shows that the experience in water resource planning is quite similar (8): Practitioners much more commonly prefer simulation approaches to optimization.

It is also relevant to note that both practitioners and faculty are agreed that there is a paucity of systems texts relevant to transportation systems analysis. This is in the face of the well-known abundance of excellent texts on optimization and operations research, both pure and applied to traffic operations and transportation methods. This is further evidence that optimization procedures, linear programming specifically, constitute only a limited portion of the methods required in transportation systems analysis.

These results confirm the impression that the prevailing predominance of optimization approaches in academic circles is not due to their overwhelming importance but to their mathematical elegance and tractability. Many faculties, for example, appear to have a solitary "systems" person, who is forever searching without much success for easy problems to knock off to prove his worth. Because optimization work can normally be carried out within a theoretical framework on an individual basis, much of the academic effort is directed toward optimization problems. Many of these problems are continually being rediscovered in the literature, are largely solved, and were not of much interest in the first place.

The other analytic elements that appear to be important to transportation systems analysis, such as modeling and evaluation, are much more subjective than optimization procedures. This implies that it is difficult to make progress along these avenues. We should not only be able to compare our judgment with that of colleagues but also, and even preferably, be able to give our opinions a real test by applying them to actual situations. This is an argument for the need for large-scale implementable studies within universities that wish to develop the systems approach. It is an argument for the desirability of a critical mass of faculty before one attempts serious research and curriculum development in transportation systems.

When individual efforts are combined, moreover, and preferably focused on specific projects, not only does it seem likely that it will be possible to develop an understanding of modeling and evaluation in transportation systems planning, but it also seems likely that we can get beyond the relatively trivial applications of optimization. Furthermore, by engaging in large-scale studies that may be implemented, faculty members will be obliged to give real concern to the problems of validation of assumptions and especially to implementation.

Multidisciplinary Programs

Because of the particular orientation of established departments within a university, it is generally reported that multidisciplinary efforts are difficult to establish. Members of any discipline, e.g., economics or political science, usually find that their immediate rewards are oriented toward that discipline. Consequently, whenever a member is forced to choose between a disciplinary activity and a multidisciplinary activity of uncertain potential, the multidisciplinary effort inevitably suffers. Worse, established departments often refuse to approve broader programs that would, inevitably, reduce their own influence and power.

The question is, then, How should we go about implementing a program in transportation systems analysis with its requisite multidisciplinary flavor? In attempting to answer this question, we should define what, precisely, we mean by a multidisciplinary effort. For example, suppose we define a multidisciplinary effort as one in which all the skills needed to attack a problem are brought together. If we agree that this is reasonable, as appears plausible, then we should recognize that engineering disciplines have long been multidisciplinary. In particular, for example, civil engineering has traditionally combined mathematics, mechanics, geology, hydrology, and thermodynamics in amounts considered sufficient to address problems the profession was confronting. In this case, there is now no problem in establishing a multidisciplinary effort.

The point is that the short-run problems of forming a multidisciplinary group, which are quite real, may evaporate over the long run. The difficulties faculty members may encounter in getting a multidisciplinary group together are not inherent to the multidisciplinary aspect of the endeavor, which we cannot change, but to its novelty and unfamiliarity, which we can eliminate.

This perspective suggests that a key ingredient to establishing a program and a curriculum in transportation systems analysis is a cogent rationale for the role and intellectual value of other disciplines. To be successful, this rationale must be convincing to the other disciplines and must ensure their support as partners in the enterprise. All too often, however, the effort devoted toward really trying to incorporate disciplines such as economics, political science, and sociology are too slight or too superficial. Much work and a precise understanding of what is important are required to establish a viable multidisciplinary effort.

HYPOTHESES ABOUT TRANSPORTATION SYSTEMS ANALYSIS

The experience so far in the use of systems analysis in transportation leads to certain conclusions about this process. Inasmuch as the evidence is still far from conclusive, these statements are cast as hypotheses. These tentative axioms are of interest both in themselves and because they imply distinct policies for undergraduate and graduate curricula in transportation systems planning and design.

Although these hypotheses appear to be true, the fact that they might not be defines some fairly specific questions for research. More attention should be specifically directed toward how and where the systems methods can be successfully implemented. Existing emphasis on research on prime systems techniques should be reduced, at least as far as transportation is concerned. Rather, it would seem more fruitful to concentrate on identifying classes of problems to which a systems approach is useful, i.e., on verifying that we know what we are doing overall.

Six hypotheses are suggested. The first two speak to where and how the systems approach should be used in transportation. The remainder focus on the kinds of skills that should be developed.

Hypothesis I

> The systems approach will make the greatest contribution in complex problems that involve many interdependent projects and the links that connect them, in particular network problems.

This hypothesis is principally motivated by the experience that indicates that the computer-based methods of systems analysis are most powerful in dealing with highly combinatorial problems. Such problems are not, of course, the only interesting problems, but they may well be the only ones that would be meaningful to include as part of transportation systems analysis.

According to this hypothesis, problems of detailed design would be unsuited for the systems approach. This appears to be confirmed by efforts to date. The evidence would indicate that, in general, attempts to use some systems analysis in this area have not led to any significant developments.

Hypothesis II

> The systems approach is most useful in planning for the overall configuration of programs and the definition of regions of optimality.

It is easy to observe that the techniques of systems analysis derive their capability to sort rapidly through highly combinatorial problems by imposing definite restrictions on the mathematical description of the problem. These assumptions consist, for example, of linearity and additivity for linear programming, of independence for dynamic programming, and so on. The techniques that use them are, thus, necessarily approximative and inappropriate for precise final design. The systems techniques are, however, most useful in sorting through many combinations and determining the dominant kinds of solutions that can then be explored in further detail.

This hypothesis implies that the analyst dealing with real problems should not waste time on a more sophisticated mathematical analysis, which probably can remove the limitations of the simpler methods (such as linear or dynamic programming) at the expense of their computational power. Rather, the analyst should devote significant effort to sensitivity analyses, both of the physical parameters of the problem, to discover areas of potential redesign, and of the evaluation criteria, to indicate how different public groups may be satisfied.

Hypothesis III

> Optimization and the more detailed simulation techniques should be used hierarchically and interactively.

This is almost a corollary to the previous statement. Because the optimization techniques are inherently approximative, they require mechanisms for examining overall plans and designs in more detail. Simulation techniques are well-suited for this purpose. They can not only easily incorporate nonlinearities and discontinuities of all sorts but also be programmed to take into account the effects of probabilistic and stochastic variations.

The relationship between optimization and simulation in a practical analysis would seem to be much more, however, than one being the backup to the other. Optimization or some other method that defines regions of overall desirable design is itself almost a necessary prerequisite to effective simulation: It provides an experimental design specifying what kind of simulation experiments ought to be performed. Conversely, the knowledge gained from testing simulation models can, by indicating which parameters are critical, help improve optimization models.

This hypothesis indicates that relatively simple optimization techniques may be appropriate for most situations. By extension, it implies that a curriculum in transportation systems analysis should, in general, not emphasize advanced programming techniques or queuing analysis. Whereas these may be elegant and appealing to mathematical sophisticates, they may have little to do with real planning and design.

Hypothesis IV

> An effective systems approach must include the skills necessary to the definition of a problem both deductively, through the use of engineering production functions, and inductively, by means of systems modeling and econometrics.

Although it is a truism that any analysis depends on the quality of the model being used, few transportation curricula now seem to deal effectively with the issue of how good modeling skills are to be developed. This hypothesis makes two specific suggestions of how this should be done. First, it recognizes that any systems analysis inevitably deals with multiattribute problems and suggests that the well-developed procedures of economics for estimating production and cost functions be exploited. Second, because a transportation system cannot be brought into a laboratory, it proposes that the economic and social science procedures for dealing with nonexperimental situations be adopted. Actual knowledge of and experience with the particular systems or problems are, of course, key to the effective use of these techniques.

This hypothesis implies that a transportation systems curriculum should incorporate some quite specific elements of microeconomics, econometrics, and causal modeling of behavior. It also provides a specific rationale for the role of economists, for example, in a multidisciplinary effort in transportation. If this rationale is accepted, economists would be seen as a central and important contributor to the effect, rather than, as often appears to be the case, as dispensable adornments to a proposal. The latter role is naturally unappealing and effectively would dissuade almost anyone from participating in a multidisciplinary effort so conceived. The role suggested by the present hypothesis, however, may be quite attractive.

Hypothesis V

> An effective analysis must be skillful in specifying evaluation criteria: Knowledge of how individual and societal preferences are developed, as through utility theory, welfare economics, and sociology, and of how they are applied in specific cases via decision analysis or game theoretic analysis of collective choice is necessary.

The motivation for this hypothesis lies in the failures of the standard benefit-cost analysis of engineering economics to deal adequately with public choice of transportation projects. These failures have been demonstrated internationally, not only in regard to urban expressway systems in the United States but also, for instance, by the evaluation for the third London airport. The reason for the failure of the standard benefit-cost analysis lies in its assumptions that

1. People have a constant value for a good, whereas they actually have a diminishing marginal utility;
2. They are indifferent to risk, whereas they are in fact generally significantly risk-averse; and
3. All elements of the public share a common system of values, which is certainly not true for large projects with important differential consequences on different communities.

To devise an evaluation procedure free from these defects requires that we learn both how to assess individual preferences and how to describe how they will combine around a preferred solution. It appears that the methods devised for measuring utility and for associating them are appropriate to this task. As might be suspected, these approaches derive substantially from political and social sciences.

As with the previous hypothesis, this statement implies that a complete transportation systems curriculum should include elements of the social sciences in key positions. In this case, however, the specific subjects to be recommended are much less clear, inasmuch as these procedures are relatively new and there is much less of a tradition for dealing with these problems.

Hypothesis VI

> The implementation of transportation systems plans requires an understanding of the power of different structures of political and governmental organizations and the effect of different management control systems.

It is reasonable to suppose that transportation systems planners should really be concerned with problem solving rather than merely with problem analysis; thus it seems clear that we must be concerned with implementation. Judging from the results of transportation systems analysis that are available so far, it would appear that the profession has not been eminently successful in this regard. Those who are concerned with the problems of implementation would ascribe such difficulties to a lack of understanding of the political dynamics on the one hand (5, 11) and to a failure to establish an adequate budgeting and control apparatus to ensure that optimal plans or designs actually get executed (10).

It would appear, consequently, that a complete curriculum in transportation systems ought to allow space for subjects dealing with state and local politics and bureaucracy as well as with the specific management techniques of program budgeting. Naturally, any reasonable graduate program soon runs out of time to offer all subjects that might be desirable. Yet, if these hypotheses are correct, these last subjects are not simply peripheral but also central to transportation systems analysis. Consequently, they should be included in the pool of core subjects that a student can choose among in defining his program.

M.I.T. EXPERIENCE

After having suggested what elements might be desirable in a curriculum for transportation systems analysis, the question remains: Can all these pieces be put together coherently? The answer appears to be yes, although the task is not simple. The M.I.T. experience is instructive in this regard.

Structure of M.I.T. Program

The program in transportation systems analysis at M.I.T. has centered around the Civil Engineering Department, where it is sponsored by the Transportation Systems Division and supported by the M.I.T. Civil Engineering Systems Laboratory. The laboratory provides a focus for work on the development and application of systems analysis in engineering planning and design. The division has been responsible for substantial work in transportation in particular.

As of early 1973, M.I.T. formed the Center for Transportation Studies embracing portions of several other departments: the Flight Transportation Laboratory, an airline operations analysis program in the Department of Aeronautics and Astronautics; the marine transportation group from the Department of Naval Architecture; elements of the mechanical and city planning departments; and the Transportation Systems Division. This new center institutionalizes the fairly close associations that have developed between these groups for research and teaching. The new center will specifically be responsible for a joint, interdepartmental program in transportation systems.

The academic program in transportation systems analysis proposes to develop the student's capabilities in three complementary areas:

1. The nature and performance of transportation systems,
2. The theories and methods of systems analysis, and
3. The understanding of the social and economic forces inherent in the environment in which transportation systems will be complemented.

As suggested by the hypothesis concerning the desirable nature of a curriculum in transportation systems, the M.I.T. program explicitly attempts to blend an understanding of transportation problems with a strong analytic competence as well as a broad sensitivity to key tools and issues in economics and social sciences.

Because no student could possibly take all the subjects that might be useful, the program is deliberately devised to be very flexible. The student is, at most, encouraged to take three or four specific core subjects in transportation and systems analysis. The other two-thirds of his program can be selected from a broad list of recommended subjects. This procedure has several advantages. On the individual level, it permits the students to grow professionally in the areas that are most productive for them. For the M.I.T. group as a whole, it provides a diversity of students who are used to attacking problems from different perspectives and who not only find it easy to work on multidisciplinary problems but also have the skills to do so.

It should also be added that the faculty members within the programs are not purely engineers. Many hold advanced degrees, even their doctorates, in different fields. City planners, lawyers, architects, economists, and a sociologist are all part of the staff. This diversity, plus the diversity cultivated among the students, means in effect that we are growing our own multidisciplinary program from within.

Recognizing that a thorough education in transportation systems really requires more than might be placed in an ordinary master's program, the M.I.T. program has been extended into the undergraduate curriculum. Since 1970, an undergraduate option, including several special subjects in transportation systems, has been available. This program is continually expanding so that students can, indeed, obtain full professional preparation in transportation systems in the 5 full years it requires to complete a bachelor's and master's program.

Transportation Subjects

The transportation curriculum has two special features. First of all, many of its subjects are jointly taught by several departments. Its core subjects in transportation, technology, demand, and economics are stressed in particular. Several specialty subjects, such as those in airport planning and management, are also taught cooperatively.

The second interesting feature, which relates directly to hypotheses I and II, is that many subjects are closely related to ongoing large-scale projects dealing with particular elements of transportation systems. These are Manheim's community values projects concerned with the development of guidelines for highway evaluation; Roos's projects implementing dial-a-bus in several communities; Sussman's projects on railroad reliability in association with several lines; and my own work on airport planning and design. These projects, each basically undertaken from a systems point of view, help identify just how and when systems analysis can and cannot be helpful in transportation.

Systems Analysis

Faculty members associated with the M.I.T. Civil Engineering Systems Laboratory are attempting to develop, along the lines sketched by the hypotheses, a common understanding of how the techniques of systems analysis should be applied to real problems. Specific areas of emphasis are stochastic systems and statistical inference for the development of systems models, the use of optimization and simulation, and evaluation procedures, including multidimensional benefit-cost analyses and decision theoretic approaches. These are being applied to large-scale, real-world studies in a number of fields, in particular, transportation.

The teaching in systems analysis in the M.I.T. program derives directly from this experience with practical problems. The research work has also led to the preparation of a number of texts that attempt to present the most relevant elements of the systems approach from the planner's point of view. Texts on probability and statistics in engineering (2) and on systems analysis (4) have already been published. A special effort is also made to relate the analysis to actual practice in the course work. This has generated a reader of case studies based on recent research (3).

Economics and Social Sciences

In addition to an active group of faculty members concerned with transportation economics and regulation, which is fairly usual, the M.I.T. program in transportation systems explicitly involves lawyers, managers, city planners, and a sociologist. In addition, students are actively encouraged to take a substantial portion of their subjects in these fields. Although it is difficult to provide a precise or meaningful estimate of the degree of this activity, it would appear that the M.I.T. effort has managed to develop and maintain an active multidisciplinary program. This may, possibly, be attributed to the intellectual success of our efforts and, consequently, to the fact that our colleagues from these fields feel as equals in the work in transportation systems.

CONCLUSION

Based on experience to date, six hypotheses have been presented concerning the role of systems analysis in transportation. These specify, first, that systems analysis is most useful for the definition of the overall configuration of transportation facilities, especially of networks. Second, they indicate that optimization, which has been a useful focus of activity, should be seen only as a search procedure to be used in conjunction with more detailed analyses. Finally, the other two main areas of concern, systems modeling and evaluation, require explicit use of the techniques and procedures of economics and the social sciences. This is a tall order to fill, but the recent M.I.T. experience indicates that it is possible.

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