

MATHEMATICAL MODELLING IN ENVIRONMENTAL DECISION-MAKING

TECHNICAL MODELING FOR POLICY MAKING: INTEGRATED MODELING OF A LARGE ENVIRONMENTAL SYSTEM

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Abstract. Increasingly, models of technical and environmental systems are being developed to support decisions related to the setting of public policy. These efforts are aimed at providing tools which can be used in a variety of roles, such as: for assessment - to test alternative assumptions about the form or parameters of a model or the impact of a proposed action; for research management - to identify and rank model components or parameters in terms of sensitivities or uncertainties according to their influence on predicted behavior; or for education and program integration - to explore how factors in complex systems interact and relate to one another. From the earliest planning stages, the design and implementation of these models must reflect their intended use and the manner in which the results will be incorporated into the policy making process. The modeling of large, integrated environmental systems for policy making creates additional constraints which require the consideration and trading off of many other factors. The model developer must reflect an understanding of who will be using the model, how they prefer to operate, what questions they are likely to want to address, how detailed or aggregated they will want information to be, and the immediacy with which they will require model results. These considerations, which can be unique for each new application of the model, are more difficult to define and constrain in the context of policy analysis than for traditional technical modeling. However, these are central to developing models with a greater probability of being used effectively in support of policy making. These considerations also carry implications with regard to selections of appropriate software and hardware systems; choice of a modeling structure; the adequacy of user interfaces; and the design of model input and output formats. An integrated modeling framework developed by the authors for the National Acid Deposition Assessment Program to simulate the linked set of physical, chemical, and biological processes associated with the environmental problem of acid deposition is examined from the perspective of assessing the intended uses and users of the model and the trade-offs inherent in planning and developing a scientifically credible model for policy analysis and synthesis.

Keywords. Environmental modeling; environmental systems; integrated modeling; model design; modeling approaches; policy making.

INTRODUCTION

More and more frequently, technical models are being used to provide information for decisions on public policy issues. This role for technical models is generally viewed as an extension of the more conventional applications of technical modeling for purposes of design or performance simulation. This is especially true with regard to the modeling of environmental systems. However, the desire to provide useful information in a particular policy making context places a number of constraints and requirements on the design and development of a technical model which generally do not arise in other modeling contexts.

This paper examines technical modeling in the context of policy making, and attempts to provide some guidance for the design and development of technical models which can more effectively support the environmental policy and decision making processes. The discussion

to follow draws heavily on the authors' experiences in developing the Acid Deposition Assessment Model (ADAM) for the U.S. Environmental Protection Agency as part of the National Acid Precipitation Assessment Program (NAPAP) (Davidson et al., 1984; Marnicio, et al., 1985; Rubin, et al., 1986).

MODELING NEEDS FOR POLICY MAKING

Policy making is typically the process by which individuals and groups with diverse interests and goals negotiate to arrive at a mutually acceptable course of action or solution to a problem. Collectively, the goals of the various groups, and the activities they undertake in an effort to obtain them, combine to influence the final policy and the process for its identification. Two principal activities associated with policy making in relation to environmental problems are policy analysis and policy synthesis. "Analysis", by definition, implies a breaking

apart or dissection of a problem into its components for a closer, more detailed examination. "Synthesis", in contrast, is based on assembling separate parts so as to form a whole.

Historically, technical models have most often been constructed for purposes of analysis. Generally, some technical or scientific process of interest is presumed to occur according to a particular algorithm or mechanism which is characterized by a linked set of component parts. Each component is then postulated to be influenced by a number of parameters which typically are dependent on some fundamental state or system variables which may or may not be controllable. Inevitably, the process of analysis drives the technical model toward a more detailed representation of the process, employing an ever broadening set of parameters, variables, and subcomponents.

Synthesis, on the other hand, starts with a set of separate parts which are believed to play some role in influencing a broader class of behavior. In order to model and explore these broader problems, a sufficient set of components must be linked in a manner which enables the required information about the general question to be developed. At times, the resultant behavior or "bottom line" characteristic of a particular component (for example, a total cost or a temporally or geographically averaged pollutant concentration) is all that needs to be reflected in a synthesis model to enable it to adequately address a particular aspect of the broader issue.

Environmental policy making generally requires both a detailed understanding of the scientific behavior and technical theories underlying a particular problem (analysis) and an integration of diverse considerations and perspectives which are important in distinguishing among the various options relative to the overall problem (synthesis). This need to incorporate and reflect the fundamental characteristics of both analysis and synthesis in a single modeling framework dictates that an appropriate balance between modeling depth and breadth be established. The desire to explore the factors that cause the various components of a problem to behave as they do and discover how these components are interrelated and influence the larger system dictates that the modeling framework address a broader scope of components at a minimally sufficient level of complexity and detail which ensures that the model results are credible and responsive to the information needs of the general question being examined.

BALANCING DEPTH AND BREADTH IN INTEGRATED TECHNICAL MODELS

Technical models can be designed to capture a range of modeling complexity. At one extreme are very simple technical models and data sets which reflect a low level of complexity and lack substantial detail. An algebraic expression with a handful of parameters which describes the essential behavior of a conceptual or judgmental model is an example of a technical model of this type. Because these models are typically small, aggregate in

nature, and have few parameters, they can easily be linked to similar models of other components of the overall problem to form an integrated framework. Such an integrated framework could be evaluated repeatedly for assessments quite quickly and economically. The underlying bases of these models are generally simple and transparent, enabling them to be easily explained to a policy maker with limited technical training and expertise in the given field. Generally, the principal shortcomings of this form of model for policy making are a lack of sufficient detail to allow a rich set of policy options to be examined and adequate technical underpinnings to be clearly credible from the engineering or scientific perspective.

Near the opposite extreme of the complexity spectrum are highly detailed technical models which are typically mechanistic in nature and reflect the state-of-the-art in scientific understanding. A long range atmospheric chemistry and dispersion model with hundreds of site-specific parameters that is capable of simulating the hour-by-hour composition of the air over all points in a broad geographic region is an example of this type of model. The sheer size and complexity involved in the calculations generally make it awkward, if not impossible, to link a related group of such models together on a single computer for assessment purposes. Repeated use of such large models is also costly in terms of time and resources. While it is generally accepted in the technical community that these models are scientifically credible and rich in detail, their complexity makes it very difficult to explain or interpret them to the average policy maker. Without a basic understanding of the model, the policy maker will not feel comfortable using its results as a factor in an important policy decision. Often, such models also are incapable of producing information that is appropriate and necessary for policy analysis. For example, the most sophisticated atmospheric transport and chemistry models cannot yet be used to calculate annual average quantities (they simulate only for periods lasting hours or days), nor can detailed mechanistic lake chemistry models be readily extended to look at regional impacts.

Somewhere between these two extremes is a level of modeling complexity which limits the size and detail of each component model so that a number of similar models can be linked and evaluated repeatedly in assessments. Sufficient technical detail would be retained, however, to ensure that the modeling results would be scientifically credible. This technical detail would be incorporated into the model in a form and manner that could be quickly and effectively communicated to the policy maker.

Unfortunately, the appropriate level of modeling depth and complexity for a set of linked component models of broad enough scope to address a responsive set of policy options cannot be prescribed a priori for all applications. The decision must be made subjectively by the modeler in light of a broad range of case-specific considerations.

The remainder of this paper addresses the design and implementation of technical models that could be effective in supporting environmental policy making. A number of these case-specific considerations will be identified to provide some basis on which to judge alternative trade-offs of modeling depth and breadth.

DESIGNING MODELS TO ADDRESS ENVIRONMENTAL POLICY ISSUES

Points to Consider

There are no recipes or checklists to follow that will guarantee success in the planning and implementation of technical models to support policy making. Every modeling effort for policy making is unique in some regard. Consequently, the following material should be viewed simply as "food for thought" to be adapted and applied as appropriate to particular modeling situations. Another point to emphasize is that technical similarities of a current problem to other environmental problems or prior analyses conducted by the modeler should not be relied on too heavily in the planning of the current model for policy making. The new modeling framework must be responsive to both the technical and the policy contexts of the current situation. Two problems which are technically similar but exist under different socio-political circumstances generally cannot be modeled in the same way, since the two models must typically provide different types of information to be used as inputs in the evaluation of their respective policy options. Thus, the modeler must always begin by acquiring a good understanding of the technical and the non-technical characteristics of the problem and its context. In this regard, it is important to keep in mind that technical models will at best provide only one of many inputs to a policy decision. Environmental policy is never established solely on the basis of algorithms or the results of model simulations, even when the "best" technical models are used.

Understanding the Problem to Be Modeled

A good modeler begins by acquiring a solid understanding of the nature and characteristics of the problem to be modeled. This statement holds true for all modeling efforts, and not just technical modeling for policy making. However, gaining a broad understanding of the problem is particularly important to modeling for policy making. Consider, for example, the problem of "acid rain". One characteristic of this problem is that it cuts across many fields of study, including: pollutant emissions; atmospheric transport and transformation; chemical effects on the environment; physical and biological responses of the exposed people, plants, animals, and materials; valuation of impacts; and the costs of mitigative or remedial actions. Second, the current state of knowledge and understanding about these various aspects of the overall problem differ greatly. Some components are relatively well understood, such as the sources of sulfur emissions; while other components, such as the susceptibility of fish to lake acidification, are replete with alternative scientific hypotheses and uncertain-

ties. Some component models, such as the one reflecting how people value the loss of aquatic resources, involve the characterization of individuals' interests and preferences. Such measures are often highly variable within and across groups. Third, the acid deposition problem is highly visible and publicized, and has become a politically polarizing issue. Finally, the broad set of technical aspects associated with the problem, and their subtleties, can be intimidating to many policy makers who come from diverse backgrounds and typically are not technically or scientifically oriented.

Reflecting the Nature of the Problem in the Model Design

Armed with an understanding of the problem and its context, the modeler can begin to specify the features and capabilities of the modeling framework required to effectively support policy analysis and synthesis. Given the characteristics of the acid deposition problem noted above, it was clear in the authors' work under the National Acid Precipitation Assessment Program that the ultimate ADAM framework should attempt to link together all of the relevant components of the problem in order to address the widest possible scope of issues and options. This included both the technical components, such as atmospheric chemistry, and the non-technical components, like the valuation of lost fishing. Second, the integrated modeling framework had to be capable of capturing the current level of understanding in each component. An ability to characterize and test alternative hypotheses and explicitly incorporate uncertainties with reasonable cost and effort was needed. Also, given the evolving nature of the current understanding about the sources and effects of acid deposition, the modeling framework had to be flexible and easily modified. Third, the component models could not openly or inadvertently reflect any political or technical biases. Fourth, the component models and the overall linked framework had to be structurally transparent and well documented, so that analysts or policy makers could quickly acquire a sense as to its general workings, and have access to a vehicle for obtaining more details if desired. Finally, the resulting set of linked models had to be capable of providing useful measures of impacts, costs, benefits, and any associated uncertainties pertaining to an identified or reasonably foreseeable set of policy options. These specifications served as the foundation for the ADAM integrated assessment model design and development effort.

Identifying the Role of the Technical Model

Every model should be planned and developed with its intended use in mind. Although the full range of eventual uses of a model can rarely be foreseen at its early stages of development, the primary use or a representative set of applications of the modeling framework can generally be identified. A technical model of the acid deposition problem could be used in three distinct roles: (1) as a vehicle for education and program integration; (2) as a preliminary screening and analysis tool; and (3) as a research management aid. The relative importance of these

various roles, which are characteristic of technical modeling to support policy making, will certainly vary from case to case.

As an educational tool, a model which integrates all of the relevant components of the problem enables individuals to explore those components which are unfamiliar to them. In addition, as is the case with NAPAP, research on the many aspects of a problem is conducted by separate groups whose focus is primarily, if not exclusively, on their own piece of the problem. An integrated framework enables the role and contribution of each separate research effort to the overall program to be demonstrated and highlighted.

Technical models which have been designed with an appropriate balance of depth and breadth also can be a valuable tool for preliminary screening and assessment of policy options. Generally, a large number of alternative policies can be identified for any problem. It would be particularly time consuming and costly to subject all potential options to a detailed assessment using complex, start-of-the-art models. However, a scientifically credible but simpler model could be used to screen a larger number of possible options to identify a subset of notable ones for closer examination. In addition, a model with the capability to characterize and test alternative scientific hypotheses, policy scenarios, and expert judgments and which could explicitly incorporate uncertainties would be a powerful tool for policy analysis, since virtually all socio-technical problems involve these features to some degree.

Finally, a set of linked component models and their associated parameters and data bases provides an ideal framework in which to organize and manage the acquisition of scientific information as it emerges from ongoing research programs. The role of model components and parameters can more easily be identified and documented through the use of an integrated framework as can missing or incomplete data. Uncertainties associated with each component also can be quantified and ranked according to their importance to the overall results, providing an aide in prioritizing research efforts.

In addition to varying from case to case, the principal use of a model can be expected to shift over the course of a given project. In the beginning, the ADAM model was used principally to educate and illustrate the overall integration of the program. Thereafter, the model was used to identify missing components and provide input to R&D planning decisions. Later, as a more complete set of scientifically credible models was developed, ADAM was able to be used in a preliminary assessment mode.

Specifying Model Design Features

Working with a solid understanding of the technical and non-technical contexts of the problem and an awareness of the various intended uses of the integrated framework, the model designer can begin to define its basic features. Generally these features pertain to: (1) the structure of the model; (2) the mode of calculation; (3) the style and format

for displaying model outputs; and (4) the factors affecting the acceptability of the model to the technical analyst or policy maker. These aspects of the model must be specified such that they adequately reflect and are compatible with the modeler, the policy maker, and the particular problem at hand.

Features relating to the structure of the model define which aspects of the problem are to be included and how they are to be linked together. These considerations affect the balancing of depth and breadth, and define the logic and flow of calculations. Design considerations relating to model structure focus on establishing linkages among the components, determining which parameters will form the bases of these linkages, and defining the dimensions of the model (for example, an appropriate level of geographic aggregation or the simulation time period).

Next, given a preliminary specification of these structural design features, the mode of calculation must be established. One determining factor in decisions about the mode of calculation is how the model and parameter uncertainties are to be treated. The modeler may opt for a "best estimate" calculation framework that ignores the uncertainties, or addresses them parametrically through sensitivity analysis. Other situations may dictate an explicit treatment of uncertainties using a probabilistic framework. The specification of the calculation mode carries with it data and operational requirements that may constrain the structure or scope of the model (e.g., the computer memory needed to accommodate a probabilistic treatment of uncertainties may limit the geographical or temporal scope of the problem that may be considered.)

The style and format for presenting model output must be carefully considered if the modeling is to provide useful and effective input to the decision making process. The modeler must: (1) identify the model results that are expected to be of value to the policy maker (e.g., are only "bottom line" results desired or are subcomponent and intermediate results also needed?); (2) establish an interface which enables the policy maker to run or direct the running of the model effectively (e.g., should an extensive menu system be developed or a dedicated programmer be hired?); (3) discover a comprehensible and informative format for displaying the results to the policy maker (e.g., should the results of a probabilistic analysis be presented in terms of confidence bands, cumulative distribution functions, probability density functions, fractile ranges, or coefficients of variation?); and (4) ascertain an acceptable turnaround time for analyses (e.g., does the model need to run on-line in real time or can runs be batched and analyzed later?)

In every modeling situation, there are a number of factors which must be considered in the early design phase to insure that the user will be comfortable with the resulting model and its use given personal or institutional preferences and constraints. Lacking this acceptance and compatibility to the local "modus operandi", the most diligent modeling effort can become totally ineffective in sup-

porting the policy making process. The list of possible factors to be considered is long, with the various items shifting in relative importance to reflect the particular modeling situation. However, the following factors typically must be considered in every case: (1) the availability and format of model documentation; (2) the degree to which preliminary results and policy implications can remain confidential; (3) the degree to which the resulting model is "user friendly"; (4) the degree of computer literacy in the policy making group; (5) the familiarity of the user to the software system employed; and (6) the extent to which the user has access to, or can acquire, the computer hardware and peripherals needed to develop and operate the model.

General Guidance for Exploring These Design Considerations

Having identified the model features that must be specified and outlined the considerations that must be addressed in modeling for policy making, a series of questions is now posed which may help the modeler focus his or her thinking and grapple with the many trade-offs and decisions required in designing and developing such a model:

- What technical alternatives and policy options are likely to be considered? What model parameters and components are needed to address these and to distinguish among them?
- Is the nature and extent of the problem and policy options well understood, or still evolving?
- Who is involved in the policy making process? Who must make the policy, sanction it, and abide by it? What are their perspectives?
- What information will the policy maker need to make the decision and justify it? What form should this information be presented in?
- When will this information be required? How often will modifications have to be made or reassessments performed?
- What institutional support (in terms of staffing, money, time, and data) would be required to run and maintain the model over time?

CONCLUSION

Technical modeling is playing an ever increasing role in environmental policy making. Decision making in this context requires tools for both analysis and synthesis of the relevant scientific data. Thus, to be useful and effective, models of large environmental systems must balance technical complexity and detail against resulting scientific credibility. In addition, such modeling frameworks must always be designed with their intended uses in mind, such as for: educational and program integration; preliminary screening and assessment; or research management. Technical models for environmental policy making must: reflect the nature and characteristics of the

system they address; link all the important components; capture the current level of understanding in each; contain no political or technical biases; be structurally transparent and well documented; and provide useful measures of impacts, costs, benefits, and their associated uncertainties. In order to be effective in supporting policy making, careful consideration must be given to specifying the structure of the overall model; the mode of calculation to be employed; the style and format for presenting model results; and any inherent features of the model and its implementation system which might affect its acceptability to its users.

Finally, while general guidance is offered for specifying the required details of a model, these features will always be highly dependent on the modeling situation and must be reconsidered in every new case.

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