Innovations in Integrated Assessment:
The Tracking and Analysis Framework (TAF)

Presented at the Air and Waste Management Conference
on Acid Rain and Electric Utilities, January 1997, Scottsdale, Arizona.

Max Henrion, Ph.D.
Richard Sonnenblick, Ph.D.
Lumina Decision Systems, Inc.
59 North Santa Cruz Ave, Ste Q
Los Gatos, California 95030
(408) 354-1841

Cary Bloyd, Ph.D.
Argonne National Laboratory
2800 Woodlawn Drive, Suite 180
Honolulu, HI 96822
(808) 539-3866

Abstract

The Clean Air Act Amendments of 1990 introduced innovation in environmental regulation by legislating trading in emissions allowances. The Tracking and Analysis Framework (TAF) is an integrated model for assessment designed to provide a comprehensive understanding of the economic and environmental effects of this legislation. TAF provides a general framework which links together a set of modules that project reductions in emissions of sulfur and nitrogen oxides, control costs, atmospheric transport, ambient pollutant concentrations and deposition, their environmental effects on visibility, aquatic ecosystems, soils, and human health, and the economic valuation of these effects. The goal of TAF is to integrate credible models of the science and technology into an assessment framework that can directly address key policy issues, and in doing so act as a bridge between science and policy. Key objectives of TAF include comprehensive coverage, agility and flexibility, transparency, scientific credibility, and explicit treatment of uncertainty. TAF achieves these objectives by an innovative combination of methods, including influence diagrams, hierarchical modules, integrated documentation, reduced-form models, probabilistic uncertainty analysis, distributed development, and progressive refinement. This paper and its companions describes the methods used, details on selected modules, and initial results.

1 Introduction

With the passage of the 1990 Clean Air Act Amendments (CAAA), the United States embarked on an acid-deposition control policy that has been estimated to cost billions of dollars. CAAA created a major innovation in environmental regulation by introducing market-based incentives — specifically, trading among electric utility companies in allowances to emit sulfur dioxide. The National Acid Precipitation Assessment Program (NAPAP) has been tasked by Congress to assess what Senator Moynihan has termed this "grand experiment". Specifically, CAAA mandates NAPAP to evaluate the status of implementation, the effectiveness, and the costs and benefits of the acid-deposition control program created by Title IV of this CAAA, and to determine whether additional reductions in deposition are necessary to prevent adverse ecological effects. To help NAPAP face this challenge, the US Department of Energy with support from other agencies has sponsored the development of an integrated-assessment model, known as the Tracking and Analysis Framework (TAF).

TAF has been developed in less than 2 years with relatively modest resources for such a comprehensive model. This rate of progress has been made possible by an innovative combination of methods for integrated assessment. In this paper, we provide an overview of TAF and outline these methods, with references to companion papers including in these proceedings, that provide more details on selected methods and modules.

1.1 General Objectives

The following are general objectives of TAF:

A framework for integrated assessment: TAF is designed to provide a comprehensive framework to address the major issues of concern, from end to end — that is, from the effects of CAAA on reducing emissions of pollutants, atmospheric transport, deposition, and environmental effects, all the way to economic valuation of the environmental benefits of emissions reductions. A variety of modules can be slotted into this framework. At present, the environmental effects addressed by TAF include visibility, aquatic ecosystems, soils, and human health. Modules for forests and terrestrial ecosystems, crops, and materials effects remain to be added.

Complete integration: TAF is designed to include all components within a unified computing environment, so that all components can be examined and evaluated together, including exploration of the interactions among components.

Agility and flexibility: TAF is designed to be run on a personal computer in a few minutes, and to allow easy modification of input assumptions and reconfiguration to assess alternative policy scenarios, as new policy issues arise and new data and science become available. It is designed to allow analysts to address new questions in hours or days rather than weeks or months.

Transparency: TAF is designed to provide the models in a form whose structure, relationships, and assumptions that can easily be inspected and reviewed. It is designed as a "glass box" rather than a "black

Scientific credibility: The models are based on the best available science and data.

Explicit treatment of uncertainty: TAF provides explicit representation of the uncertainties due to limitations in our scientific understanding, lack of data, and model precision.

1.2 Modeling Methods

In order to achieve the objectives just listed, we have adopted the following set of methods, which are described in more detail below or in companion papers:

Influence diagrams: Influence diagrams provide a graphical representation for display of the qualitative structure of models.

Modular structure: We organize the model into a hierarchy of modules so that each module is simple enough to be easily understood.

Integrated documentation: We integrate documentation explaining the variables and their representations into the computer representation.

Reduced-form models: Most modules are reduced-form models — that is, simplified models fitted to more detailed, scientific models. They derive their scientific credibility from the quality of their fit to the detailed models.

Probabilistic analysis of uncertainty: We use probability distributions to represent variability, uncertainty due to lack of scientific knowledge or data, and imprecision due to model approximations.

We use Monte Carlo and related methods to propagate and combine these distributions to assess the implied uncertainty in the results, and to compare the importance of the various sources of uncertainty. These methods and results are described in the companion paper in these Proceedings (Sonnenblick and Henrion, 1997).

Distributed model development: The team that has developed TAF includes about thirty scientists and modelers in groups in different organizations at ten sites around the U.S. We have developed a variety of techniques for specification, communication, coordination, and integration to facilitate these groups in developing modules so that they can be integrated into TAF, making effective use of the Internet. We describe these methods in a companion paper in these Proceedings (Sonnenblick, Henrion, and Soo Hoo, 1997).

Progressive refinement: The team has developed TAF as a series of prototypes of increasing sophistication and refinement, progressively reviewing and refining each to create the next version.

Several of these methods have been used in the development of other integrated-assessment models. In adopting and refining the entire set of methods, we have found significant synergies among them, leading to what we believe comprise some important innovations in integrated-assessment methodology. Our use of many of these methods has been facilitated by our use of Analytica, general modeling software for quantitative modeling and integrated assessment, developed by Lumina. Analytica (Henrion et al., 1996) provides a variety of features used in TAF, including influence diagrams, hierarchies of modules, integrated documentation, and Monte Carlo simulation.

2 Overview of TAF Modules

A comprehensive assessment of the costs, benefits, and effectiveness of the CAAA Title IV requires consideration of many issues. Figure 1 shows the top level of TAF as an influence diagram. Each of the nodes on the diagram represents a module of TAF.
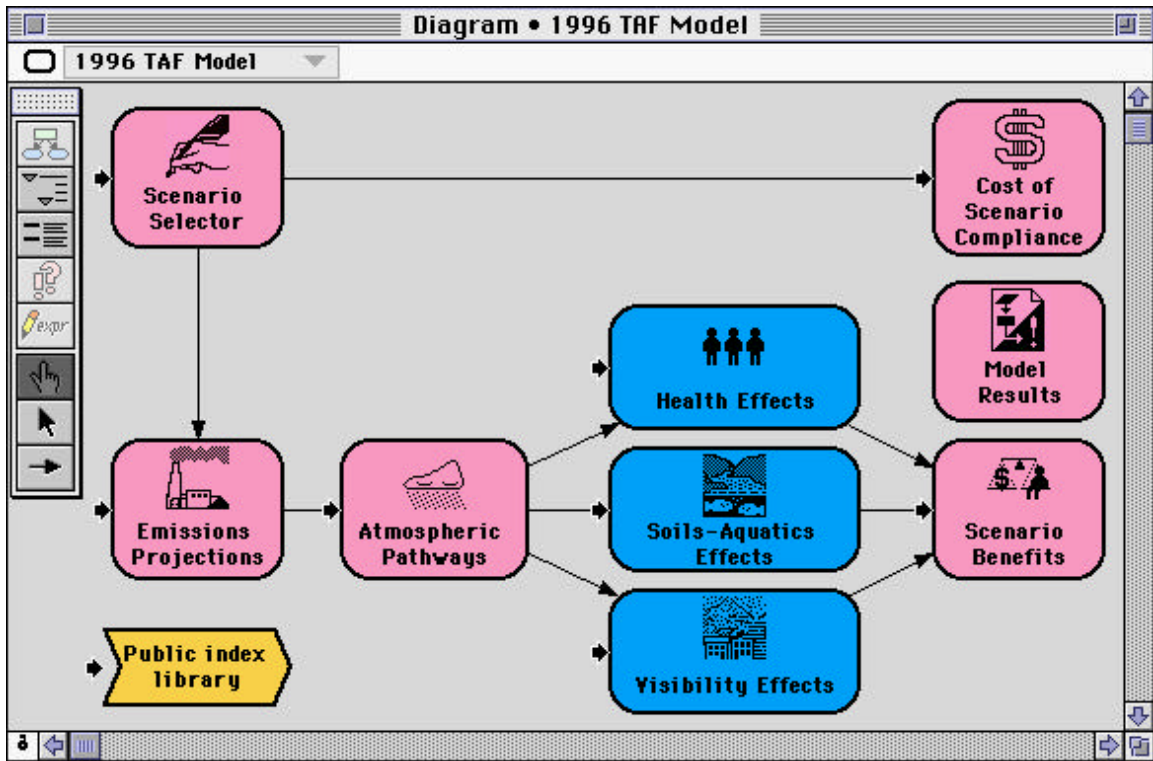
Figure 1: Top-level influence diagram window showing key modules of TAF, a computer screenshot from the TAF prototype

The node on the top left is the scenario selector that allows the model user to select one or more scenarios for projecting future emissions, and hence to assess and compare effects of those emissions. The user can specify his or her own scenario, making assumptions about future growth rates in emissions, by pollutant type (SOx and NOx), and source region. Alternatively, the user can select a predefined scenario, from recent EPA projections, or estimated projections from one of sixteen scenarios defined by TAF's emissions module. These sixteen scenarios are based on combinations of Phase I caps only and Phase 2 caps, with and without trading in emissions allowances, and with alternative assumptions about future electricity demand growth rates, and power plant retirement ages.

TAF currently contains ten modules, developed by over thirty people, at ten different sites, including four consulting firms, three national laboratories, two universities, and a nonprofit foundation. Table1 lists modules and contributors that have been developed or are under development for TAF. For more details on many of these, see the separate summary and detailed documentation.

Table 1: Authors and organizations responsible for TAF Modules, integration and project management

Modules	Authors	Organizations
Emissions scenario selector	Rich Sonnenblick, Kevin Soo Hoo and Max Henrion	Lumina Decision Systems, Inc. (Lumina), Los Altos, CA
Emissions projections and cost 1	John Molberg and Jeff Camp	Argonne National Laboratory (ANL), Argonne, IL
Emissions projections and cost 2	Jayant Kalagnanam & Stuart Siegel	Carnegie Mellon University, Pittsburgh, PA (CMU)
Atmospheric pathways and deposition	Jack Shannon Ron Marnicio	ANL Foster-Wheeler (FW), Dublin, Ohio
Visibility effects	Jack Shannon and Jeff Camp	ANL
Aquatics effects	Mitchell Small and Rajarishi Sinha Tim Sullivan	CMU E&S Environmental Chemistry, Corvallis, OR
Soils effects	Pat Ryan	Science Applications International Corporation (SAIC), for Oak Ridge National Laboratory (ORNL). Oak Ridge, TN
Crops effects	Edward Rykiel and Ron Kickert	Battelle Pacific Northwest Laboratories (PNL), Richland, WA
Health effects	Alan Krupnick and Deirdre Farrell	Resources for the Future (RFF), Washington, DC
Valuation of effects	David Austin, Dallas Burtraw, and Erin Mansur	RFF
Project management	Cary Bloyd, John Formento, and Guenter Conzelmann	ANL
Integration framework and Public Index Library	Max Henrion, Rich Sonnenblick and Kevin Soo Hoo	Lumina

3 Model Transparency and Organization

A common complaint about computer models – be they scientific or policy models – is that they are too complicated and too poorly documented to be understood, verified, or trusted. Typically, model documentation is created and updated separately from the computer model, with the result that it becomes inconsistent with the model it is supposed to document. In some cases, models are proprietary, and their developer wishes to keep their internal structure secret. Since a major objective of TAF is to support communication and coordination among scientists and policy analysts, an essential requirement for TAF is that the models be documented clearly and consistently.

3.1 The module hierarchy

TAF employs features of Analytica to display the model as a hierarchy of influence diagrams and to integrate model documentation in the same computer representation used for computation. In Figure 1

we showed the top-level influence diagram, including the key modules and arrows indicating the dependencies among these modules.

Each module may contains its own submodules. Each module consists of a diagram, showing the key inputs and outputs, and submodules containing the details of the model. These submodules are themselves arranged hierarchically, as illustrated in Figure 2.

Clicking the mouse on one of these nodes in the diagram opens up the diagram for the model it contains. This model hierarchy in TAF extends down to six levels in parts of TAF. It is also possible to display the model hierarchy in the form of an indented outline, as shown in Figure 3.
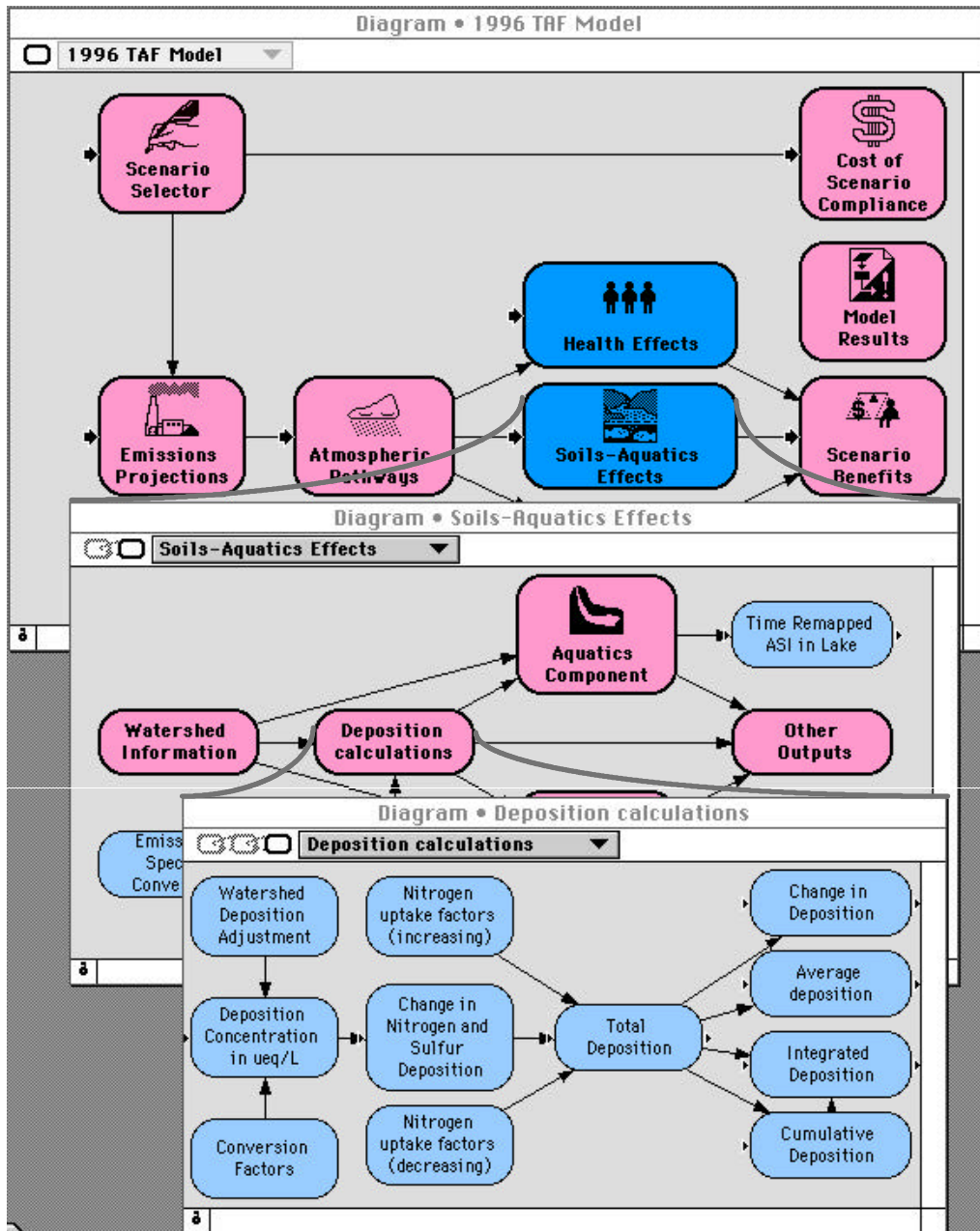

Figure 2: An example of the module hierarchy in TAF. Double clicking the mouse on a module node (thick outline) opens up the diagram for that module. We repeat to see the third level down the hierarchy. Parts of TAF contain up to six levels.

6

Each variable in a model is represented in a diagram by a node with a thin outline. Variables that are defined as uncertain, using a probability distribution are represented by oval nodes. Other variables are represented as rounded rectangles. Index variables are represented by parallelogram nodes.

3.2 Integrated documentation

Each variable in TAF is documented by a card (Object window), containing a set of attributes describing the variable, as illustrated in Figure 4. The card shows the variable class, name, units of measurement, description, definition (mathematical relationship for calculation), list of inputs and outputs, and, optionally, a reference to the publication or authority on which the definition is based. The card also lists the inputs and outputs of the variable. When the definition of a variable is specified or modified, Analytica automatically updates the lists of inputs and outputs, and the arrows in the parent diagram to reflect any changes in the dependency relationships.
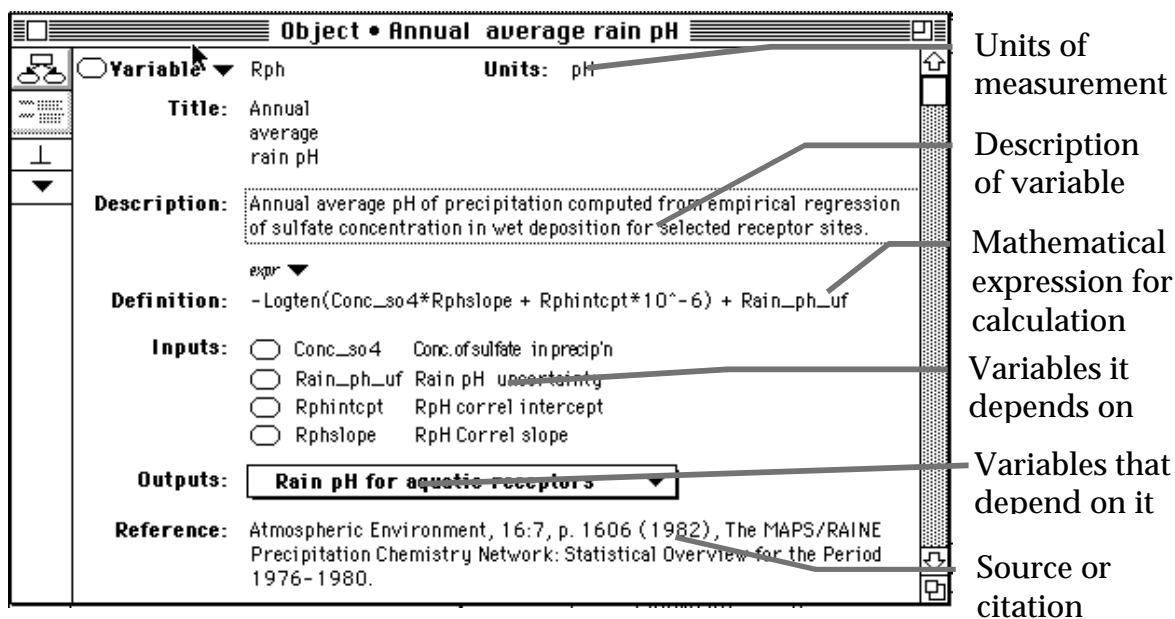

Figure 4: Each variable is documented internally with object window. The card shows key information about the variable, including its mathematical definition, and a source or citation.

3.3 Access via the Internet

The most recent version of TAF can be downloaded from the Internet by members of the TAF development team. Documentation describing TAF and the underlying science is available on the World Wide Web.

4 Scientific Credibility and Reduced-Form Models

Previous attempts to develop integrated assessment models have sometimes been criticized as lacking sound scientific foundations due to the degree of simplification (Balson & North, 1982; Alcamo et al., 1987). The challenge is to reconcile the need for models to be based on the best available scientific data

and models, yet to be small, agile, flexible, and comprehensible. TAF meets this challenge by building most modules as reduced-form models based directly on the best available detailed scientific model or data.

Reduced-form models (RFMs) are simplified models, intended to approximate the behavior of larger, more complicated **full-form models** or data sets. RFMs are simplified in containing fewer variables, less causal detail, or higher levels of aggregation. Their performance is calibrated against or fitted to the performance of the detailed models. Hence, the quality of the approximation can be measured, and the uncertainty from the approximation can be compared with uncertainty from other sources. In practice, the approximation uncertainty introduced by the simplification for the RFMs in TAF is usually dwarfed by the inherent uncertainty in the full-form model. In these cases, the loss in precision from the RFM is negligible.

In integrated assessment, it is generally necessary to link several models together – the outputs of one are matched to the inputs of the next. Typically, problems arise because the detailed models are at different levels of aggregation. For example, emission projections may be by season for each power plant; but, the atmospheric transport model may need emissions on a daily basis aggregated by 20 kilometer grid-square. It also often happens that the file formats and platforms are incompatible. Moreover, the models are so large that it is too expensive and time-consuming to run them for many different scenarios, especially to handle uncertainty using Monte Carlo or other techniques. It is often impractical to reconfigure and rerun them every time a new policy problem arises. The use of RFMs lets one avoid these problems, provided the RFMs are designed explicitly to use compatible levels of aggregation and file formats.

RFMs may be developed or formulated in a wide variety of ways. As examples, we describe the approaches employedfor the atmospheric transport module and the acquatic ecosystems module.

4.1 RFM for atmospheric transport module

The atmospheric pathways module of TAF is an RFM based on results from the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP), the detailed long-range atmospheric transport model developed at Argonne National Lab (Shannon, 1981). The RFM consists of source-receptor matrices, normalized to unit emissions at each source. The normalization allows the model to be applied to any emissions scenario. Since ASTRAP generates ambient concentrations and deposition rates that are linear in emission rates, this normalization involves no additional approximation. The 60 sources are centroids of US States, Canadian provinces, and North Mexico. Temporal aggregation is by season and year. Transport matrices are provided for dry and wet deposition for SOx and NOx. Specific receptors have been selected for the visibility, aquatics, crops, and human health effects. Figure 5 shows the top left corner of a source-receptor matrix, for Ambient SO2 in Winter. See the documentation on the Atmospheric Pathways module for more details.

Diagram • Ambient Concentrations

Seasonal Average Ambient Species Concentration S/R Matrix → Seasonal Average Ambient Species Concentration → Annual Average Ambient Species Concentrations

Other Species Regression Coefficients

Summer PM-10 Concentration

Seasonal Dry Ion Ambient Concentration Regression Parameter

Edit Table • Seasonal Average Ambient Species Concentration S/R

Edit Table of Seasonal Average Ambient Species Concentration S/R

Seasons ⇩ Winter

Ambient species ⇩ Ambient SO2

60 source regions ▼

TAF 1995 receptors ▼

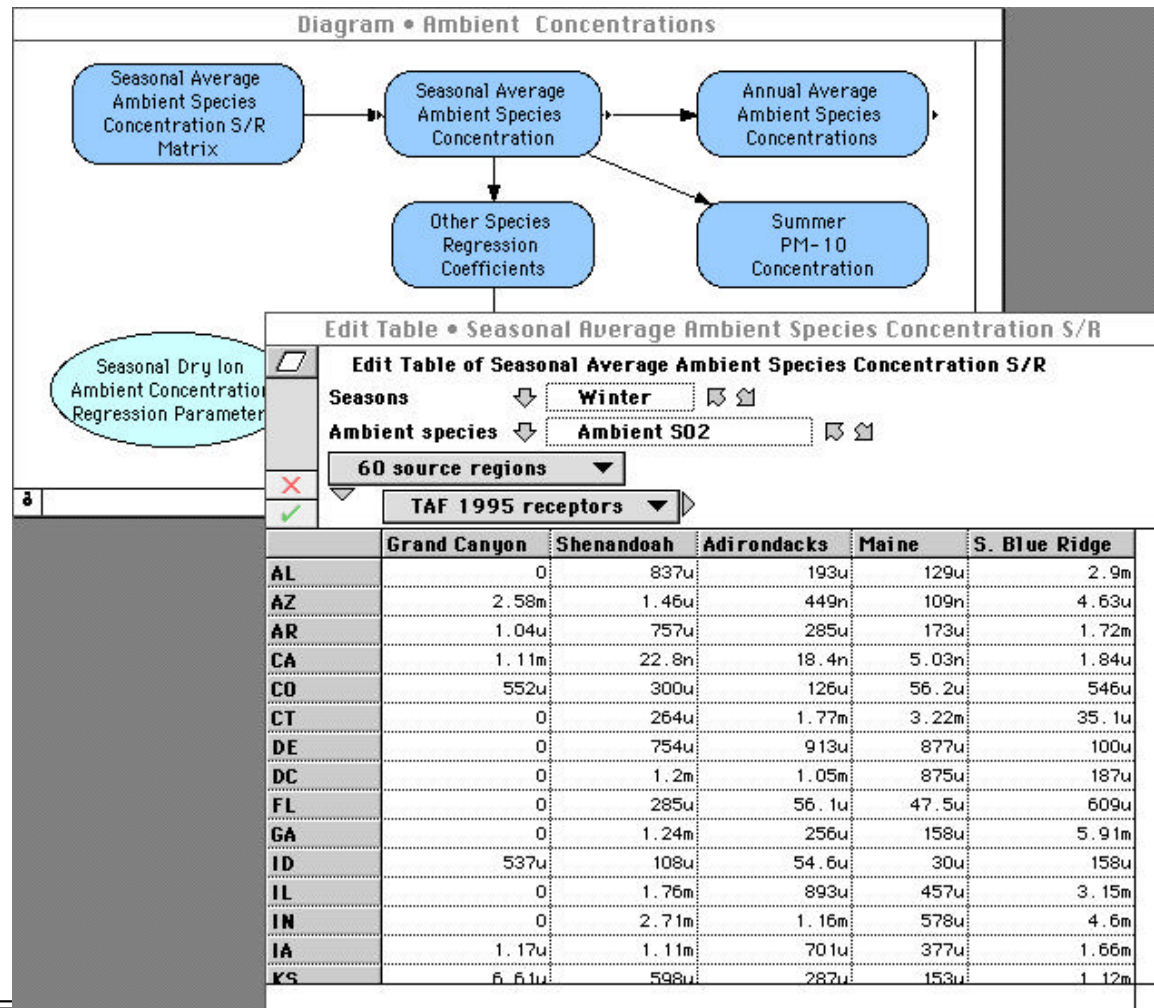|	Grand Canyon	Shenandoah	Adirondacks	Maine	S. Blue Ridge
AL	0	837u	193u	129u	2.9m
AZ	2.58m	1.46u	449n	109n	4.63u
AR	1.04u	757u	285u	173u	1.72m
CA	1.11m	22.8n	18.4n	5.03n	1.84u
CO	552u	300u	126u	56.2u	546u
CT	0	264u	1.77m	3.22m	35.1u
DE	0	754u	913u	877u	100u
DC	0	1.2m	1.05m	875u	187u
FL	0	285u	56.1u	47.5u	609u
GA	0	1.24m	256u	158u	5.91m
ID	537u	108u	54.6u	30u	158u
IL	0	1.76m	893u	457u	3.15m
IN	0	2.71m	1.16m	578u	4.6m
IA	1.17u	1.11m	701u	377u	1.66m
KS	6.61u	598u	282u	153u	1.12m

Figure 5: The lower window shows part of the normalized transport matrix by source plant and receptor region, as a detail of the diagram in the upper window. The two-dimensional transport matrix displayed is for Winter and ambient SO2, and is a slice from a four-dimensional array, indexed by four seasons and four ambient species.

Shannon (1997) has compared the performance of ASTRAP with RADM, a nonlinear tranport model, and actual observations for annual average atmospheric concentration at selected receptor sites in the East U.S. Figure 6 shows an example comparison with regression lines fitting the observations to predictions for each model. Both models appear to underestimate the observations on average. Both models show a similar quality of fit to the data. Since ASTRAP is a linear model, it generates ambient concentrations and deposition at each receptor that are proportional to the emissions at the sources. Therefore, representing it by normalized transport matrices, as in TAF, introduces no additional approximation imprecision for given time period (seasons). In other words, there is no approximation uncertainty introduced by the RFM beyond the model uncertainty inherent in the detailed model on which it is based. Moreover, the uncertainty of the latter appears to be no more at the selected levels of aggregation over space and time than RADM, which is significantly more complex model than ASTRAP.
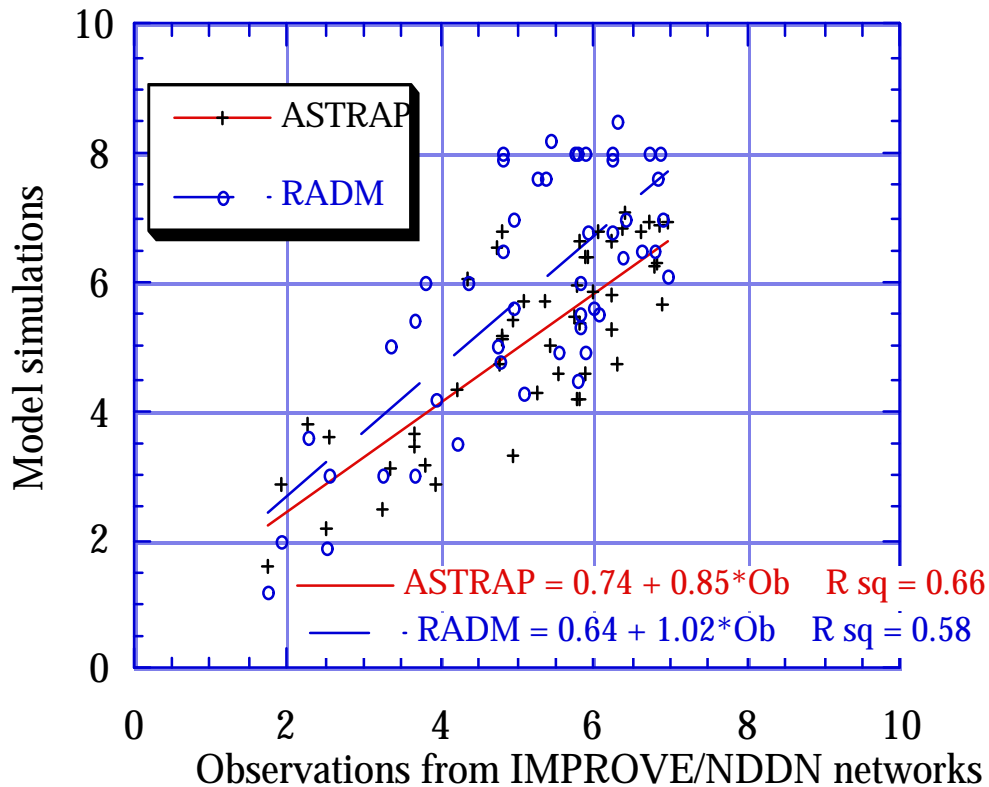
Figure 6: A comparison of predictions by ASTRAP (the TAF module) and RADM (another more detailed transport model) with actual observations of annual average concentrations of atmospheric sulfate ($\mu g/m^3$) in the eastern U.S. in 1990.

4.2 RFM for Aquatics model

The effects of acid deposition on soils and aquatics are based on a series of RFMs. Lake, stream, and watershed soil chemistry are predicted by RFMs based on approximations of output from an improved version of the Model of Acidification of Groundwater in Catchments (MAGIC) (see Cosby et al, 1995a, b; Sullivan and Cosby, 1995a; Sullivan et al. 1996B). MAGIC is a state-of-the-art, lumped-parameter model that uses chemical equilibrium and mass balance equations to predict changes in lake and soil chemistry in response to acid deposition. It is designed to operate at the watershed spatial scale and the temporal scale of years to decades, not considering short-term effects, such as storms. MAGIC for NAPAP was calibrated with watersheds in the Adirondacks.

The TAF reduced-form aquatics model uses a linearized approximation of the most recent version of MAGIC (Sullivan and Cosby, 1995a). It assumes an exponential approach to equilibrium ANC concentrations in the soil water of each watershed (Small et al, 1995). This equilibrium value changes as a result of cumulative deposition. A fraction of direct runoff is also assumed for each lake. Nonlinear regression was used to estimate the parameters of the TAF RFM model from the MAGIC calibration runs. An example of the fit of the RFM to MAGIC is shown in Figure 7 for acid-neutralizing capacity (ANC) and in Figure 8 for calcium. There are systematic errors in both cases, but these are dwarfed by other sources of uncertainty.
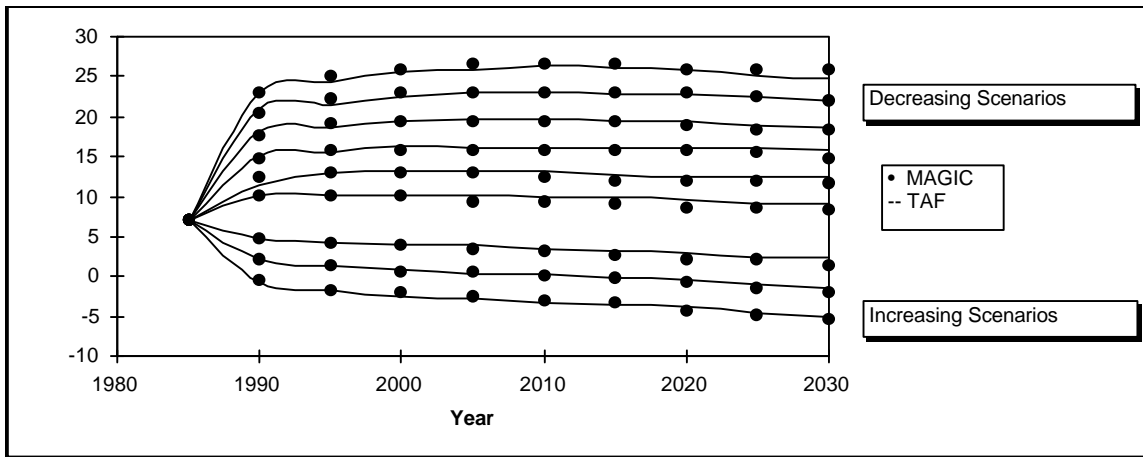
Figure 7: Fit of TAF Reduced-Form Model to MAGIC: Acid-Neutralizing Capacity (ANC) for Watershed 1A1-012 (results are for increasing deposition scenarios of 10-30% and decreasing deposition scenarios of 10-60%)
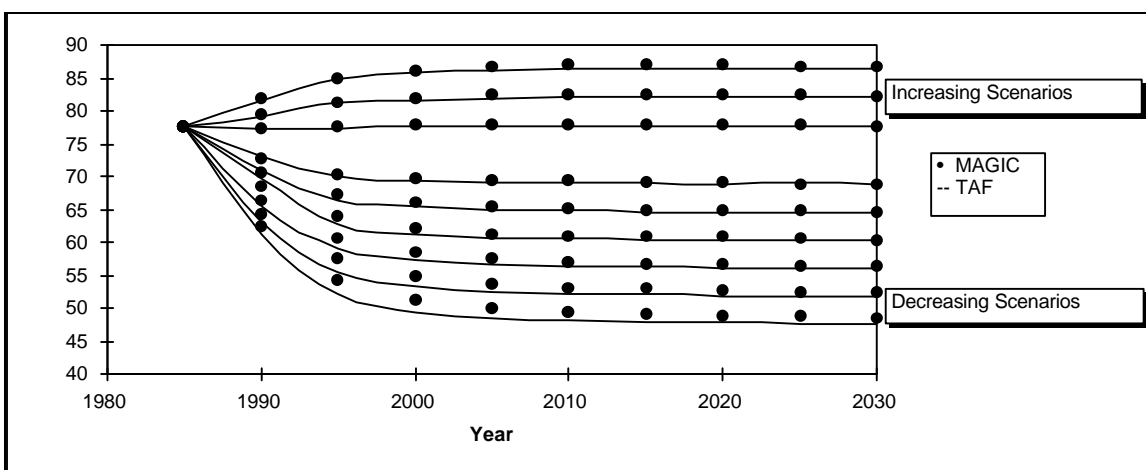

FIGURE 8: Fit of TAF Reduced-Form Model to MAGIC: Calcium for Watershed 1A1-012 (results are for increasing deposition scenarios of 10-30% and decreasing deposition scenarios of 10-60%)

5 Progressive refinement

Model development is, or should be, a learning process. It requires many decisions about the level of detail and aggregation of each variable, making compromises between accuracy and practicality, between detail and computer time and memory, between the policy questions of concern and the pragmatic limitations on what questions the model can address. Finding the best tradeoffs is a major challenge, even for the most experienced modelers. The most satisfactory results are obtained when the modelers can revisit decisions in the light of experience with early versions of the model — expanding, simplifying, and refocusing models as the process continues. We call this process *progressive refinement*. Progressive refinement can be compared with the more conventional *single-pass approach* to model development and integration.   Past attempts to integrate modules in a single pass have failed due to the lack of opportunities to identify and resolve incompatibilities among modules and inconsistencies in model assumptions or structure. More generally, a single-pass approach overlooks the central role of iterative review and refinement that we regard as essential to the process of collaborative model development.

We adopted progressive refinement as our approach to TAF from the beginning. We were able to start with an early model named ADAM, developed for NAPAP in the mid 1980s at Carnegie Mellon University. In 1993, Derek Winstanley, then the director of NAPAP, asked Cary Bloyd, Max Henrion,

11

and Ron Marnicio to develop a revised prototype integrated assessment model, based on ADAM, that came to be known as TAF. During the present phase, starting in the Fall of 1994, TAF has undergone three major cycles of refinement:

- Phase 1: Development of module specifications.

- Phase 2: Development of modules according to these specifications with internal mathematical structure and a mixture of dummy and real data

- Phase 3: Development of refined modules with realistic data.

At each phase, modules were developed by the module teams. When the modules were complete, they were transferred electronically via Internet to the Lumina integration team for review and integration. The integration team examined each module for consistency with the integration guidelines, including RAM requirements, clarity of layout and documentation, and consistency with module specifications, as well as the plausibility of substantive model assumptions. They modified modules where necessary providing detailed comments to their authors. They then integrated the modules to run in combination. Finally, they returned the revised modules to their authors for further refinement. They also made the integrated model available for review by the entire TAF team via the World Wide Web. so that all TAF developers could download the integration to examine and analyze each module in the context of the entire model. In many cases, modules went through several minor revisions within each major phase, with intermediate versions being exchanged with the integration team for review and refinement.

It is clear that these multiple cycles of progressive refinement were essential in obtaining a fully integrated model. In principle, each module team, by adhering strictly to the module specifications and RAM budget allocations, might have developed a module that could have been satisfactorily integrated in Phase 3. In practice, however, they did not adhere strictly to these guidelines, and felt that they needed to modify the initial specifications and RAM budgets as they gained experience with their module in context. In many cases, we believe that these modifications have resulted in significant improvements to the model. But, it is only by dint of these iterated cycles of review, integration, and refinement that this has been possible.

6 Implementation in Analytica

TAF has been implemented in Analytica, a software package for creating, analyzing, and communicating quantitative models to support decision making under uncertainty. Analytica was developed at Lumina, as a successor to Demos, based on technologies originally developed at Carnegie Mellon University. Analytica was designed to support the development of both small and large quantitative modeling projects, including the integrated assessment of complex environmental problems. Analytica provides the following features that have been employed in TAF:

- influence diagrams as an intuitive visual way to create and communicate models. Example influence diagrams are shown in Figures 1 and 2.

- hierarchical modules to organize complex models as a hierarchy of modules which are each small enough to be comprehensible and manageable. Each TAF module is an Analytica module, containing within in a hierarchy of submodules to organize its substructures.

- integrated documentation, to include the units, description, definition, inputs and outputs of each variable, as hypertext, integrated with the computational structure of the model (Figure 4).

- intelligent arrays as a way to compute with multidimensional tables with power and flexibility. Many variables have up to four or five dimensions. See Figure 5 for an example of a two-dimensional slice from a four-dimensional array.

- probabilistic modeling and Monte Carlo simulation for the representation and analysis of uncertainty. See Sonnenblick & Henrion (1997) for more details on how TAF uses these facilities.

Analytica is currently available on Macintosh computers, and an engine library that executes models under Windows95.

7 Conclusions

An intensive peer review of TAF by twelve scientists in December 1995, concluded that TAF was generally successful in meeting its objectives. The team has provided considerable refinement in the last year to address remaining concerns and improve the analysis.

Hierarchical influence diagrams have proved valuable as a visual tool to support transparency for organizing and communicating complex models. Analytica's tools for integrated documentation and array abstraction have also proved helpful. Members of the TAF team and reviewers have been able to scrutinize model structure and assumptions using the built-in model diagrams and documentation.

TAF is small enough to run in a few minutes, allowing multiple Monte Carlo runs for comprehensive uncertainty analysis, and flexible enough to be rapidly reconfigured to address new policy issues, yet derived from credible, detailed scientific models. The key to reconciling these apparently conflicting goals has been the development of RFMs for key modules. We have demonstrated that the model approximation involved in the RFMs is generally overwhelmed by other sources of uncertainty. In other words, the relatively small size and simplicity of TAF imposes no important loss of precision in the results that it generates. (See companion paper Sonnenblick and Henrion, 1997, for more details.).

The challenge of developing a model as a collaboration among ten groups distributed over ten organizations and geographic sites, has required us to develop some new methods and tools, in some cases adopted from the practice of software engineering. These methods include a variety of means for supporting information sharing among collaborators as well as specific technical tools, such as module specifications, the public index library, and the RAM budget.

The general approach has been of progressive refinement, in which each module and the integrated model are developed as a series of versions, starting with module specifications, being progressively refined in response to review and critique by other members of the team. The current version of TAF is the result of four major cycles of refinement, each comprised of a number of minor cycles.

Hitherto, we believe that the development of TAF has clearly met objective 1, to support coordination among scientific researchers. A major benefit of the approach has been to develop a better mutual understanding and much closer collaboration among diverse groups of scientists and policy analysts involved in studying various aspects of the problem. How well TAF can support objective 2, to support communication with policy makers, and objective 3, to provide guidance for prioritizing research needs, remains to be tested in future phases of the project.

We believe that the methods and tools that we have developed and the experience that we have gained in developing TAF could be of value to other teams involved in the collaborative development of models for integrated assessment. Other domains of application might include integrated assessments for regional or local air-pollution policy, and for international environmental problems, especially for global climate change.

In a further effort to share TAF-related research, information on the TAF project, including draft models and the Demos modeling software, is being made available over the World Wide Web via Internet (http://www.lumina.com/taflist).

Acknowledgments

References

Alcamo, J., Amann,M., Hettelingh, J.P, Holmber, N, Hordjik, L., et al "Acidification in Europe: A simulation model for evaluating control strategies", *Ambio.* 16(5), 232-245, 1987.

Balson, W.E. and North, D.W. " Acid deposition: Decision Framework", EA-2540, prepared by Decision Focus, Inc for the Electric Power Research Institute, Palo Alto, CA, 1982.

Dowlatabadi, Hadi & M. Granger Morgan, "Integrated Assesment of Climate Change" Science, Vol 259, 26 Mar 1993: 1813-4.

Cosby, B.J., Wright, R.F., Hornberger, G.M., and Galloway, J.N. "Modeling the effects of acid deposition: Assessment of a lumped parameter model for soil water and stream water chemistry", *Water Resources Res.* 21(1), 51-63. 1985.

Henrion, M. et al., *Analytica User Guide,* Lumina Decision Systems, Los Altos, Ca, Oct, 1996.

Henrion, M. & B. Fischhoff, "Assessing Uncertainty in Physical Constants", *American Journal of Physics*, 54, (9), September, 1986, pp. 791-798.

Henrion, M. & M. G. Morgan, "A Computer Aid for Policy and Risk Analysis", *Risk Analysis*, Vol 5, No 3, 1985, pp. 195-208.

Henrion, M. and Silva, J.S, "The Potential Cost Savings from Information Technology in the US Healthcare System", Lumina Decision Systems, Palo Alto, CA, 1993.

Labieniec, P.A., M.J. Small, and B.J. Cosby "Regional Distributions of Lake Chemistry Predicted by Mechanistic and Empirical Lake Acidification Models" Regional Acidification Models, Springer Verlag, 1989

Lumina Decision Systems, Inc. *Demos Reference Manual,* Los Altos, California, 1993, 230pp.

Lumina Decision Systems, Inc. *Analytica User Guide,* Alpha version, Los Altos, California, November, 1995.

Morgan, M. Granger and Max Henrion, *Uncertainty: A Guide to the Treatment of Uncertainty in Quantitative Policy and Risk Analysis*, Cambridge University Press, New York, 1990.

Rubin, E.S. , M.S. Small, C. Bloyd, R. Marnicio, & M. Henrion, "Atmospheric deposition asssessment model: Application to regional aquatic acidification in eastern North America ", Chapter 14 in *Impact Models to Assess Regional Acidification*, J. Kamari (ed.), Kluwer Academic Publishers: Dordrecht, The Netherlands, 1990, pp 253-284.

Rubin, E.S., M.J. Small, C.N. Bloyd, and M. Henrion, "Integrated Assessment of Acid-Deposition Effects on Lake Acidification", *J. Environmental Engineering*, Vol 118, No 1, Jan/Feb, 1992, p120-134.

Shannon, J.D. "A model of long term average sulfur atmospheric pollution, surface removal, and net horizontal flux", *Atmos. Env.* 15(5), 689-701. 1981.