Integrated Modeling Environment Project

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IIASA
International Institute for
Applied Systems Analysis
A-2361 Laxenburg, Austria

Tel: +43 2236 807
Fax: +43 2236 71313
www.iiasa.ac.at

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Marek Makowski[1]

Abstract

The strategic goal of the Integrated Modeling Environment (IME) Project is to build capacity to meet IIASA's growing needs for integrated modeling support where commonly known methodology and/or general-purpose modeling tools are inadequate. The long-term aim is to strengthen IIASA's in-house capabilities and competitive advantage in modeling complex problems. The strategic goal is decomposed into three objectives: (1) Integrate and extend modeling methods and tools developed to address individual demands into an advanced Web-based modeling environment adapted specifically to the needs of IIASA's programs. (2) Develop methods and tools for policy analyses to cope with inherent endogenous uncertainties and risks with potential catastrophic consequences, proper representation of abrupt changes, spatial and temporal distributional heterogeneities, vulnerabilities, and robust solutions. (3) Develop methodology and tools for integrated model analysis aimed at combining the capabilities of different methods (such as various types of simulation, optimization, multicriteria model analysis, sensitivity analysis) with data mining technology.

The relevance of the IME activities to IIASA objectives and mission will be achieved by a continuation of the long-term collaboration with (1) IIASA applied programs that need new modeling methods, and (2) networks of leading researchers in the pertinent fields of science.

Introduction

Methodological activities[2] at IIASA fall into two categories. First, each IIASA program develops and exploits disciplinary methodology pertinent to its research; often such methodology includes modeling methods and tools: either standard (general-purpose) or discipline-specific. Second, many of IIASA programs develop models for which established modeling methods or standard modeling tools are not adequate. IME addresses a part of (defined implicitly by the characteristics of modeling activities presented in points 1 to 6 below) the needs for methodological research and support of the second category.[3]

The relevance of advanced modeling methodology to policy issues is justified by the characteristics of the models developed for analyzing policy-related problems, and thus support the corresponding decision-making processes. Such models have growing complexity and size, and are often developed by integrating models and/or data developed by different teams; they also need to properly treat uncertainty and risks, as well as spatial and temporal distributions. Moreover, the modeling processes supporting policy making have to meet the strong requirements of: credibility, transparency, replicability of results, integrated model analysis, controllability (modification of model specification and data, and various views on, and

[1] In collaboration with Yuri Ermoliev, the Institute Scholar, whose research will become a key part of the IME project.
[2] Methodology is understood (following Webster's dictionary) as the system of principles, procedures, and practices applied to a particular branch of knowledge.
[3] Other areas of methodology are addressed in the research plan of IIASA's Dynamic Systems Program.

interactive analysis of, results), quality assurance, documentation, controllable sharing of modeling resources through the Internet, and efficient use of resources on computational Grids.

Mathematical modeling of a complex problem is actually a network of activities involving interdisciplinary teams collaborating closely with experts in modeling methods and tools. In some cases such expertise is available within IIASA's programs; often however new methods and/or software need to be developed. IME addresses these needs and will develop methods and provide support for modeling activities in the case of:

(1) Models with a complex structure using large amounts of diversified data, possibly from different sources.

(2) The need for robust strategies to account for a proper treatment of spatial and temporal distributional aspects, vulnerabilities, inherent uncertainty and endogenous risks affecting large communities and territories.

(3) Demand for integrated model analysis, which should combine different methods of model analysis for supporting a comprehensive examination of the underlying problem and its alternative solutions.

(4) Stronger requirements for the whole modeling process, including quality assurance, replicability of results of diversified analyses, and automatic documentation of modeling activities.

(5) Requirement of a controlled access through the Internet to modeling resources (composed of model specifications, data, documented results of model analysis, and modeling tools).

(6) Demand for large computing resources (e.g. large number of computational tasks, or large-scale optimization problems, or large amounts of data).

The use of established modeling methods and general-purpose modeling tools cannot adequately meet the requirements of such modeling activities.[4] Thus there is a need to advance modeling methodology to address these requirements, and to directly apply the research results through long-term collaboration with several IIASA programs.

IIASA's niche in modeling methodology is implicitly defined on the one hand by the methodology legacy, needs and opportunities, and on the other hand by available resources. In recent years IIASA has concentrated on selected issues of global change which are explored by the development and analysis of mathematical models. There are many competitors in this field, hence combining the excellent substantive research in IIASA's applied programs[5] with innovative methodology and techniques for modeling is nowadays one of the key necessary conditions for playing a leading role in global change research. Methodological research is now a small fraction of IIASA research activities, and thus has to focus on research that is not only valuable in terms of its scientific results but also can be directly implemented while helping to solve challenging modeling problems faced by applied programs.

The proposed research plan is based on the current needs of IIASA programs for novel modeling methodology. The experience from activities summarized in Attachment A not only provide a solid basis for the IME project but also characterize a strong synergy between scientific achievements and their applications.

[4] This statement is justified in the section headed Background below and supported by past activities summarized in Attachment A.

[5] By applied we mean programs that deal with a substantive (e.g., environmental, technological) problem of global change.

Background

Modeling State-of-the-Art

Because of the unquestionable success of mathematical modeling in problem solving, various modeling paradigms[6] have been intensively developed over the last few decades. In this, to a great extent case-study-driven process, a growing tendency to focus on specific methodologies and tools was observed. As a result, different types of models were developed (e.g., static, dynamic, continuous, discrete, deterministic, stochastic, set-membership, fuzzy) with a view to best representing different problems by a selected type of model. Moreover, different methods of model analysis (e.g., simulation, optimization, soft simulation, multicriteria model analysis) have been developed as the best-possible support for various types of model analyses for different purposes and/or users.

Because of space considerations no specific comments on particular modeling paradigms will be made here. Such comments, and a more extensive bibliography, can be found in e.g., [60, 73]. Here the discussion is restricted to the two types of problems for which there are no established modeling methods and tools: first, proper treatment of endogenous uncertainty, and adequate modeling of spatial and temporal heterogeneity; second, methodology for development and analysis of models build to support analysis and solution of complex problems.

Policy-making addressing global change issues pose new challenging methodological problems for a proper treatment of uncertainty. The prediction of overall global climate changes requires not only a prediction of the climate system, but also an evaluation of endogenous socioeconomic, technological, and environmental processes and risks. Traditional approaches rely on real observations and experiments. Yet, there are no adequate observations in existence for new problems, and learning-by-doing experiments may be very expensive, dangerous, or simply impossible. The main issue is the lack of historical data on potential abrupt irreversible changes occurring on extremely large spatial, temporal, and social scales. Moreover, extreme events playing such a decisive role are, on average, evaluated as improbable events during a human lifetime. A 1000-year disaster (i.e., an extreme event that occurs on average once in 1000 years) may, in fact, occur tomorrow. Thus, it is not rational to perform a proper evaluation of complex heterogeneous global-change processes on “average”. The traditional models in economics, insurance, risk-management, and extreme value theory are based on exact predictions and evaluations.[7] For example, the established extremal value theory deals primarily with independent events and assumes that these events are quantifiable by a single number [12]. Catastrophes are definitely not events quantifiable in this sense. They have significantly different spatial and temporal patterns and induce heterogeneity of losses and gains which exclude the use of average (aggregate) characteristics. Globally, an average resident may even benefit from some climate-change scenarios, while some regions may be simply wiped out.

The most important scientific challenge in addressing the above summarized problems is to develop proper methods for comparative analysis of the feasible decisions and to design robust policies with respect to the uncertainties and risks involved. Although exact evaluations are impossible, the preference structure among decisions can be a stable basis for a relative ranking of alternatives. This issue is discussed in more detail in [38] along with other open research problems related to proper treatment of irreducible uncertainty, catastrophic risks, spatial and temporal heterogeneity, downscaling, and discounting.

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[6] A scientific paradigm, as defined by Kuhn [42], embodies the consensus of a scientific community on an approach to a class of problems. A more detailed discussion on modeling paradigms is presented in [52].

[7] For example, standard insurance theory essentially relies on the assumption of independent, frequent, low-consequence (conventional) risks, such as car accidents, for which decisions on premiums, claims estimates and the likelihood of insolvency can be calculated from rich historical data.

Global-change policy-making needs to be supported also by analysis of complex interdisciplinary problems which in turn requires adequate modeling technology, i.e. application of all pertinent modeling paradigms in an integrated manner. However, the modeling state-of-the-art does not support multi-paradigm modeling. Each modeling paradigm embodies a great deal of accumulated knowledge, expertise, methodology, and general-purpose modeling tools specialized for solving various problems peculiar to each modeling paradigm, such as GAMS, AMPL, AIMMS, MPL, and object-oriented modeling systems (e.g., ASCEND). Such tools have been developed over the years and will continue to be developed and used for applications that can be adequately supported by a corresponding modeling paradigm. However, there are problems, and the corresponding models (such as IIASA's RAINS model) that demand modeling technology that cannot be provided by general-purpose tools. Moreover, modeling resources are fragmented, and using more than one paradigm for the problem at hand is too expensive and time-consuming in practice. Geoffrion [30] formulated the principles of structured modeling thus providing methodological framework for the integration of various paradigms. Unfortunately, the proposed integrating framework has been to a large extent ignored, and most modeling paradigms have been developed somewhat separately.

The low productivity of model-based work compared with the high productivity of data-based work has already been discussed in [30]. In the case of databases, DBMSs are mature and well-established, and there is a broad agreement on the definitions of the abstract data models, as well as on the operations (e.g., those featured in SQL) to be supported for working with these data. This broad agreement has made it possible to efficiently use data from different sources because DBMS products of high quality are available and widely used. It is therefore strange that professional-quality DBMS techniques are not routinely used in most modeling systems although it is generally agreed that dealing properly with models of a realistic size requires the use of modern DBMS technology, which has advanced immensely and is now well integrated with the Web.

Continuous progress in the foundations of modeling, and in database management, and new opportunities emerging from the network-based, platform-independent technologies offer a solid background for providing the desired modeling support needed for management, policy makers, research, and education. Arguments supporting this statement are summarized e.g., in [7, 9, 10, 11, 32, 26, 71]. However, modeling technology is still at the stage where data-processing technology was before the development of DBMS. The data-management revolution occurred in response to severe problems with data reusability associated with file-processing approaches to application development. DBMSs make it possible to efficiently share not only databases but also tools and services for data analysis that are developed and supplied by various providers and made available on computer networks. Data processing was revolutionized by the transition from file processing (when data was stored in various forms and software for data processing had to be developed for each application) to DBMS. The need to share data resources resulted in the development of DBMSs that separate the data from the applications that use the data. The modeling world has not yet learned this lesson: almost every modeling paradigm still uses a specific format of model specification and data handling.

Science and Policy Context

Dantzig summarized in [8] the opportunities and limitations of using large-scale models for policy making. Thanks to the development of algorithms and computing power today's large-scale models are at least 1000-times larger; thus, large-scale models of 1970s are today classified as rather small. This, however, makes the Dantzig's message relevant to practically all models used today, not only for policy-making but also in science and management.

Today's models are not only much larger. The modeled problems are more complex (e.g., by including representation of knowledge coming from various fields of science and technology), and many models are developed by interdisciplinary teams. The complexity, size, model development process, requirements for integrated model analysis form the main arguments justifying the needs for the new modeling methodology to be developed by IME project. More detailed arguments (including overview of the standard modeling methods and tools) supporting this statement are available in [52].

One of the most important issues in decision making (not only in policy-making) is the proper treatment of uncertainty. A thorough scientific policy analysis of on-going socioeconomic, technological and environmental global change processes raises new methodological problems that challenge traditional approaches and demonstrate the need for new methodological developments for proper treatment of inherent, practically irreducible uncertainties and "unknown" risks that may affect at once large territories and communities. Large-scale potential catastrophic impacts and the magnitudes of the uncertainties that surround them particularly dominate the climate-change policy debates [39, 61, 64, 66, 74]. More detailed discussion of the relevance of a proper treatment of uncertainty to policy making is presented in [38].

How IME will Enhance the Modeling State-of-the-Art

The presented overview of the state-of-the-art shows the limitations of traditional modeling methods and general-purpose modeling tools developed to deal with one of the standard problem-types through a particular modeling paradigm. The requirements summarized in points 1 to 6 above demand a qualitative jump in modeling methodology: from supporting individual modeling paradigms to supporting a *Laboratory World*[8] in which various models are developed and used to learn about the modeled problem in a comprehensive way. The truth is that there are no simple solutions for complex problems, thus learning about complex problems by modeling is in fact more important than finding an "*optimal*" solution. Such a Laboratory World requires integration of various established methods with new (either to be developed to properly address new challenges, or not yet supported by any standard modeling environment) approaches needed for appropriate (in respect to decision-making process, and available data) mathematical representation of the problem and ways of its diversified analyses. Therefore, to be able to adequately meet the demand for advanced modeling support one indeed needs to develop and apply novel modeling methodologies.

IME will enhance the modeling state-of-the-art by advancing methods for:

- Structured modeling supporting the whole modeling cycle of complex problems by interdisciplinary teams working at distant locations.
- Proper treatment of irreducible uncertainty, catastrophic risks, spatial and temporal heterogeneity, downscaling, and discounting.
- Integrated modeling environment combining human expertise with modeling resources (models, data, modeling tools) for model-based support to analyzing and solving complex problems.

The participants in this special project are well positioned to develop the needed capacity, and to meet the corresponding research challenges. Over the years, many IIASA activities have required new modeling methods and tools; this has prompted IIASA and its collaborators to develop and apply novel modeling paradigms for adequate representations of complex problems, effective treatment of uncertainty and risks with potential catastrophic consequences, methods and tools for supporting the whole modeling cycle, including analysis and the management of huge amounts of data, and specialized algorithms for solving the computational tasks involved. The IME Project plans to adapt and extend several methods and tools developed

[8] Originally proposed by Dantzig, see e.g. [8, 37].

for supporting different modeling activities (summarized in Attachment A), develop new methods and tools needed, and integrate all of them into a modeling environment combining human expertise and modeling tools; in such a way they will not only become suitable for IIASA's current needs but can be expanded for future challenges.

Strategic Goal and Objectives

The strategic goal of the IME Project is to build the capacity needed to meet IIASA's growing needs for integrated modeling support where commonly known methodology and/or general-purpose modeling tools are inadequate. The long-term aim is to strengthen IIASA's in-house capabilities and competitive advantage in modeling complex problems.

To meet this strategic goal, the project has the following objectives:

(1) Integrate and extend modeling methods and tools developed to address individual demands into an advanced Web-based modeling environment adapted specifically to the needs of IIASA's programs.

(2) Develop methods and tools for policy analyses to cope with inherent endogenous uncertainties and risks with potential catastrophic consequences, proper representation of abrupt changes, spatial and temporal distributional heterogeneities, vulnerabilities, and robust solutions.

(3) Develop methodology and tools for integrated model analysis aimed at combining the capabilities of different methods (such as various types of simulation, optimization, multicriteria model analysis, sensitivity analysis) with data mining technology.

Each of these objectives corresponds to one of the three research activities (presented below) which are composed of distinctive and achievable tasks. In this way, the IME project contributes to IIASA's overall objectives by improving the methodologies of the applied programs addressing strategic issues of global change.

Research Framework

The methodology for achieving the IME objectives will build on the activities documented in Attachment A, in particular the project's experience and expertise in:

- Long-term collaboration with those applied programs that need new modeling methods, trust that modeling specialists can help and therefore are willing to "invest" resources needed for a common understanding of the modeling issue, and for testing new alternative approaches.
- Up-to-date knowledge of new developments in scientific fields pertinent to advance modeling methodology; this in turn requires active participation in research networks. While modeling support certainly requires software engineering skills, the actual challenge is to advance research in related areas of mathematics and operations research.

This in-house experience will be enhanced by the participation in the proposed research of guest research scholars and participants of the Young Scientists Summer Program (YSSP), which has proven effective in the past. Moreover, the opportunities offered by the IIASA PostDoc program will also be explored. Further, IME will develop the capacity necessary for providing qualitatively better modeling support than the existing collection of methods and tools. Collaborative activities with various programs (see the section on Networking and Collaborators) will strengthen IIASA's in-house capabilities in complex modeling activities.

Additionally, models and data implemented in Structured Modeling Technology (SMT), see below, will be accessible through the Web, substantially enhancing collaborative modeling activities both in-house and with external partners and users of selected models. Finally, IME will continue to invite leading researchers from its collaborative networks for short visits to IIASA to work on more specific problems, and to share their experience through seminars and informal meetings.

Two types of tangible results from IME can be expected: (1) research results published in peer-reviewed journals and books, and presented at conferences; and (2) direct application of the results through long-term collaboration with several IIASA programs. The summary of past activities (see Attachment A) shows that difficult and non-standard problems arising from IIASA's complex real-world applications have been very good triggers for advances in modeling methods and tools. Many novel methods developed by the participants of the IME project, and applied in collaboration with IIASA programs have not only contributed substantially to the quality of modeling work, but have also been recognized as significant advances by the mathematics, economics, and operations research communities. Thus, a very desired synergy has been achieved between advancing methodological research and applying novel results in collaborative work with disciplinary programs. This forms a solid base for the proposed research and the planned collaboration.

Thus, publications will continue to contribute to maintaining IIASA's reputation in these fields, and also to the objectives defined in Article II of IIASA's Charter.[9] In addition to articles it is planned to write two books, focused on selected modeling issues, and on coping with uncertainty. Each of these books will be composed of three parts: methodology, tools and techniques, and applications. The third part of each book will consist of chapters co-authored by colleagues from various IIASA programs. It is also planned to continue organizing the two series of workshops (on Complex System Modeling, and on Uncertainty) that have a long tradition of facilitating scientific contacts, and also result in good publications. In addition, IME will be an active participant in the newly established IIASA Methodology Forum, which will facilitate sharing experiences and increasing collaboration between the different programs.

The IME Project has limited resources therefore no organizational sub-division is planned. However, in order to provide accountability of the objectives defined above, this plan is broken down into three, mutually linked research activities outlined in the following sections. The tasks listed under the activities comprise all those that would be required for full implementation of the plan. However, with the currently foreseen resources only some of these tasks can be implemented and are prioritized.

Research Activities

Structured Modeling Technology (SMT) Activity

The development, maintenance and exploitation of models is comprised of interlinked activities, often referred to as a *modeling process*. Such a process should be supported by modeling technology that is a craft of systematic treatment of modeling tasks using a combination of pertinent elements of science, experience, intuition and modeling resources, the latter being composed of knowledge encoded in models, data, and modeling tools. Thus the key to a successful modeling undertaking is defined by the appropriate choice of "*a combination of pertinent elements*". This can only be achieved through long-term and efficient collaboration of researchers advancing disciplinary methodology with those progressing modeling methodology, the latter keeping contacts with recent developments in operations research.

[9] *"The institute shall undertake its own studies into both methodological and applied research in the related fields of systems analysis, cybernetics, operations research, and management techniques."*

The Structured Modeling principles proposed by Geoffrion [30, 31] form a solid methodological basis for SMT, which aims at supporting the entire modeling process composed of:

- Analysis of the problem and development of the corresponding model (symbolic) specification.
- Collection and verification of the data to be used for calculating the model parameters.
- Definition of various model instances (composed of a model specification, and a selection of data defining its parameters).
- Diversified analyses of instances.
- Documentation of the whole modeling process.

The SMT prototype developed in 2004–2005 (see Attachment A for a summary) has been successfully tested by its application to the IIASA RAINS model, which has a rather complex structure (including indexed sets of indices), and is a medium-size LP model. Thus, IME has proven that SMT is able (after implementation of access control to resources) to support interdisciplinary modeling activities by teams working at distant locations. There is, however, a number of challenging research and software engineering issues and tasks that will have to be solved in the coming years in order to fully exploit the potential of SMT; these include:

(1) Controlled access to modeling resources (composed of model specifications, data, results and modeling tools).

(2) Automatic documentation of the entire modeling process to be available on demand in diversified forms that fit the different needs of various users of SMT.

(3) Diagnostics of semantic correctness of model specification.

(4) Handling (including visualization and documentation) of large amounts of data used for model development and resulting from diversified methods of model analysis.

(5) Effective and efficient exploitation of computational grids.

(6) Exploiting preprocessing-type techniques for generating easier-to-solve representations of selected types of optimization problems.

(7) Providing context sensitive help for SMT users.

(8) Support for upscaling and downscaling methods enabling consistent implementation of different local and global scale models.

(9) Support for specification of: (a) models based on advanced techniques for coping with uncertainty and risks; (b) non-linear models, and (c) qualitative models.

(10) Support for merging models developed separately into one model, and for extracting a model part for separate analysis.

(11) Adapting knowledge engineering methods to support efficient use of the diversified capabilities of SMT.

(12) Use of ontology[10] for supporting model specification by users not familiar with mathematical programming.

(13) Reconnaissance on how knowledge science[11] can help in a better exploitation of mathematical modeling for both integration and creation of knowledge on complex problems.

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[10] A formal specification of a shared conceptualization (consisting of concepts, relations, functions, etc.); see e.g., [5].

[11] A new field dealing with modeling and management of knowledge creation and integration processes, see e.g., [65].

The above list is sorted according to an evaluation of current IIASA needs, taking into account the resources (including time) needed for their implementation. With the expected resources and proposed duration of this project, full implementation of the first seven topics could be expected, and exploratory activities are envisaged for the remainder. However, the priorities may change according to the needs of IIASA's programs, and new research topics will be added if required contingent on available resources. Moreover, the research topics of coping with uncertainty and of integrated model analysis are closely related to the proposed research on SMT. However, each of them has specific characteristics and these are summarized in the separate activity descriptions below.

Coping with Endogenous Uncertainty and Risks Activity

Global socioeconomic, technological and environmental changes raise new scientifically challenging problems requiring new concepts and approaches. These problems are characterized by inherent endogenous uncertainties and risks, large temporal-spatial scales and heterogeneities, interdependencies and nonlinear interactions that may potentially lead to abrupt changes with irreversible catastrophic impacts. Traditionally, scientific approaches to uncertainty rely on observations, repetitive experiments and predictions. However, for new problems historical data may not be available and experiments may be extremely costly and dangerous, leading to poor evaluations and predictions.

A key task in these cases is to design robust policies with respect to uncertainties and risks on various temporal and spatial dimensions. In particular, an important task is the development of integrated stochastic models that combine reduced spatial catastrophe generators, multi-agent accounting frameworks, vulnerability modules, risk reducing and risk spreading decisions together with fast adaptive Monte Carlo optimization. These models allow for the design of robust policies which take into account uncertainties in an explicit and consistent way by using *hard* data from historical observations, the results of possible experiments, model simulations, *soft* expert opinions and perspectives of future learning. In contrast to statistical robustness an essential feature of robust decisions is their sensitivity (responsiveness, discontinuity) to low probability extreme events. In other words, robust strategies cannot be rationally evaluated by ignoring extreme events, e.g., by using average values. To achieve such responsiveness new approaches to a joint decision and data analyses are required. Traditionally, input data is analyzed independently of the goal for a forthcoming decision analysis. However, decisions may cancel out effects of uncertainties and often require only specific details of inputs. Therefore, a joint data and decision analysis may significantly reduce the data requirement, if the latter is coupled with the goals and feasibility of decisions. One also needs to properly address the spatial and temporal distributional aspects (such as change in incomes or productivity, exposure to risks, etc.), for various agents and using diversified criteria (including fairness and equity considerations).

The research topics under this activity are implicitly defined by the following collaborative tasks to be undertaken with several IIASA programs:

(1) Jointly with the Land Use Change and Agriculture (LUC) Program: the development of new downscaling and upscaling methods. As a first step a fast sequential downscaling procedure will be analyzed to enable a recovery of local land use processes from the available aggregate regional and global data. Further steps will include a proper treatment of uncertain input data and prior distributions of downscaling and upscaling procedures for designing robust strategies by a proper treatment of spatial and temporal heterogeneities and vulnerabilities. Specific attention will be paid to ensuring the consistency of integrated models composed of submodels of different scales.

(2) Jointly with LUC: development of spatial catastrophic risk management models for analyzing vulnerability of flood prone regions in Ukraine aimed at designing robust solutions taking into account potential impacts of climate changes.

(3) Jointly with several programs participating in the cross-program activity Greenhouse Gas Initiative (GGI): the formulation and analysis of a CO_2 emission stabilization problem under uncertainty and possible abrupt changes and extreme risks; where special attention will be given to robust strategies and the development of the needed methods and software. New approaches to endogenous discounting will also be developed to ensure robust use of strategies with respect to extreme events and catastrophic risks.

(4) Jointly with Transitions to New Technologies (TNT) Program: development of endogenous technological growth models under uncertain increasing returns and risk attitudes of different agents.

(5) Jointly with the Energy Program and Transitions to New Technologies (TNT) Program: the development of stochastic versions of dynamic global energy models aiming at generation of CO_2 emission scenarios and robust CO_2 emission stabilization strategies.

(6) Jointly with the Energy Program, the Forestry (FOR) Program and the Atmospheric Pollution and Economic Development (APD) Program: development of models for CO_2 emission trading processes.

(7) Possible modeling collaboration with the new Risk and Vulnerability Program.

According to the needs of, and resources available from, the collaborating programs some of the above topics will be elaborated and implemented in more detail than other topics, for which only exploratory activities will take place. Joint activities on the first three topics have already started, thus most likely they will be elaborated quite extensively. The next three topics have been proposed based on past joint activities and recent discussions but the extent of future activities still needs to be discussed. The last topic is new and still needs to be explored.

Integrated Model Analysis Activity

Model analysis is probably the least researched element of the modeling process. This results from the focus that each modeling paradigm gives to a specific type of analysis. However, the essence of model-based decision-making support is precisely the opposite; namely, to support diversified ways of model analysis and to provide efficient tools for various comparisons of solutions. Such an approach can be called Integrated Model Analysis.

A typical model for supporting decision-making has an infinite number of solutions, and users are interested in analyzing trade-offs among a manageable number of solutions that correspond to various representations of their preferences, often called the preferential structure of the user. Thus, an appropriate integrated analysis should help users to find and analyze a small subset of all solutions that correspond best to their preferential structures that typically change during the model analysis. Structured Modeling Technology will provide the computational technology framework for the analysis, but there are three types of problems (briefly summarized below) that call for innovative research: (1) integration of various paradigms of model analysis; (2) extracting knowledge from large sets of solutions; (3) efficient solution of computational tasks (either resource demanding, or numerically difficult, or large sets of simple jobs).

For a truly integrated problem analysis one should actually combine different methods of model analysis, such as: classical (deterministic) optimization (and its generalizations, including parametric optimization, sensitivity analysis, fuzzy techniques), multicriteria model analysis, stochastic optimization and Monte Carlo simulations, classical simulation, soft simulation, and several of its generalizations (e.g., inverse simulation, softly constrained simulation). However, no modeling tool supports such a complete analysis, and the development of separate versions of a model with tools supporting different modeling paradigms is typically too expensive. Thus, the IME Project plans to work towards finding a satisfactory alternative solution to this problem.

The second research challenge is to develop and implement a methodology for a comprehensive analysis of large sets of solutions. Here, the project plans to explore the applicability of various data mining and knowledge engineering techniques, and either adapt some of them or develop new methods to extract and organize knowledge from large sets of solutions, and supply users with this knowledge in a form that will help further problem analysis.

The third set of research issues is related to efficient and robust organization of computational tasks typically needed for large-scale models, and includes:

- Efficient support to handle a large number of solutions resulting from various types of analyses of large models.
- Adaptation of specialized optimization algorithms for badly conditioned problems.
- Support for exploiting the structure of huge optimization problems that need to be solved on computational grids.[12]

Under the planned resources and proposed duration of this project, full implementation of the following tasks could be expected:

(1) Integration of selected (according to the needs of programs using SMT) methods of model analysis.

(2) Efficient support for handling a large number of results.

(3) Adaptation of specialized optimization algorithms.

(4) Exploration of new methodologies for a comprehensive analysis of large sets of solutions.

Multicriteria Model Analysis: NEEDS Project

Making rational decisions for any complex problem requires various analyses of the tradeoffs among the conflicting goals that are used for measuring the results of applying various decisions. Multicriteria Model Analysis (MCMA) methods are probably the most efficient methodology for such analyses. IIASA was a leading center of MCMA in the period of 1980–1995. Since 1995, albeit with minimal resources, IIASA was able to maintain its expertise and develop modular tools in this area. This resulted in IIASA's participation in the EU funded Integrated Project NEEDS approved for 2004–2008, where IIASA leads one workpackage and participates in another. In 2005 IIASA will make a requirement analysis and propose the most suitable method for MCDA. The proposal will be based on a survey of approaches and tools that are suitable for both the model to be used for scenario generation and the needs of stakeholders. The scope of IIASA's activities beyond 2005 will be defined after the discussion of the requirement analysis.

2006 Work Plan

Almost all of the IME Project's activities are driven by the needs of the IIASA collaborating programs. However, neither IME nor any of those programs are in a position to finalize plans before our and their research plans beyond 2005 are approved. With this reservation, and based on past experience and current plans the following IME activities are planned for the first 12 months:

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[12] This item is contingent on additional resources, and on the availability of external collaboration with partners having suitable experience.

(1) Enhancements of SMT according to the needs of its users. This will most likely include:

- Experiments with exploitation of a computational grid.
- Prototype of controlled access to modeling resources (composed of model specifications, data, results, and modeling tools).
- Prototype of diagnostics of semantic correctness of model specification.
- Providing context sensitive help for SMT users.

(2) Exploration of use of ontology in SMT.

(3) Analysis of uncertainty of prior distributions and stability of sequential downscaling procedure; development of methodology for explicit treatment of uncertainty and risks within sequential downscaling procedure.

(4) Prototype of a spatial catastrophic risk management model for analyzing vulnerability of flood prone Tisza River basin, Ukraine.

(5) Analysis of risks measures properly capturing effects of catastrophes risks, irreversibility, abrupt changes, delayed responses, and learning on climate-change decisions.

(6) Exploration of methods for a proper handling specifics of spatial, temporal, and social heterogeneities with respect to losses, goals, social values, and exposures to hazards by treating distributional aspects as probabilistic distributions enabling use of stochastic optimization approaches and software.

(7) Explore possibility of development of a dynamic MESSAGE-type stochastic global energy model aiming at generation of CO_2 emission scenarios and robust climate-change decisions.

(8) Exploration of data-mining techniques to analysis of parametric optimization of RAINS model.

(9) Participation in the EU-funded NEEDS project (the details will be decided in Autumn 2005).

(10) Active participation in the activities of IIASA's Methodology Forum.

(11) Organization of at least two workshops (on Advances in Complex System Modeling, and on Decision Making under Uncertainty) that will contribute to activities of IME collaborative networks.

Most of these tasks will result in either scientific papers (mostly written jointly with colleagues from collaborating programs) or in the development of specific software.

Networking and Collaboration

The philosophy behind the work of the IME Project is that it is mainly driven by the needs of the other programs at IIASA. Hence, internal and external collaboration is a major component in determining the project's activities. Internally, collaborative activities with at least the following IIASA programs are planned:

(1) APD: applications of SMT to the RAINS/GRAINS family of models.

(2) Programs participating in GGI: applications of SMT for data repository, and for selected models to be contributed to the GGI Policy Framework.

(3) Energy and TNT: stochastic energy and technology models.

(4) LUC: downscaling and upscaling methods, spatial and temporal modeling of land use and vulnerability, and flood catastrophe risk case study in Ukraine.

(5) Programs participating in GGI: CO_2 emission stabilization under uncertainty.

(6) TNT: endogenous growth models under uncertain returns.

(7) DYN: Institute-wide methodological activities, especially on modeling complex problems.

External collaboration includes joint activities with the following institutions, where various types of formal agreements exist:

(1) EU-FP6 Integrated Program NEEDS: we lead a work-package on Multicriteria Model Analysis of energy models.

(2) National Institute of Telecommunications, Warsaw, Poland: collaboration on the development of SMT.

(3) Two Centers of Excellence (Kyoto University, and Japan Advanced Institute of Science and Technology, both Japan): agreements of collaborative research.

(4) University of Ottawa, Canada: applications of SMT for qualitative modeling in medicine.

The project also plans to continue, and possibly extend, two collaborative networks consisting of leading experts in fields of:

(1) Advanced methods and tools for complex system modeling, and

(2) Stochastic programming, modeling uncertainty and risk, spatial land use modeling.

These networks have been maintained for about two decades and have resulted in many various activities, including publications and conferences. The most intense collaboration and participation is with:

- Germany (Federal Armed Forces University, Munich; RWTH, Aachen),
- Japan (Environmental Research Center, Tsukuba; Kyoto University; National Institute for Environmental Study, Tsukuba; Osaka University; The Japan Advanced Institute of Science and Technology, Hokuriku; The Japan Institute of Shinayaka System Engineering, Kyoto),
- Norway (Norwegian University of Science and Technology, Tronheim; University of Bergen),
- Poland (National Institute of Telecommunications, Warsaw; Systems Research Institute of the Polish Academy of Science, Warsaw; Warsaw University of Technology),
- the Netherlands (Center for World Food Studies, Amsterdam; EURANDOM, Eindhoven; Eindhoven University),
- Sweden (KTH, Stockholm),
- Ukraine (Glushkov's Institute of Cybernetics, Kiev), and
- USA (University of California; University of Florida).

Selected Publications

ERMOLIEV, Y., ERMOLIEVA, T., MACDONALD, G., and NORKIN, V. Stochastic optimization of insurance portfolios for managing exposure to catastrophic risks. *Annals of Operations Research 99* (2000), 207–225.

ERMOLIEV, Y., ERMOLIEVA, T., and NORKIN, V. Economic growth under shocks: Path dependencies and stabilization. In *Micro Meso Macro: Addressing Complex Systems Couplings* (Abisco, Sweden, 2004), H. Liljenström and U. Svedin, Eds., Abisco Book.

ERMOLIEV, Y., MICHALEVICH, M., and NENTJES, A. Markets for tradeable emissions and ambient permits: A dynamic approach. *Environmental and Resource Economics*, 15 (2000), 39–56.

MAKOWSKI, M. A structured modeling technology. *European J. Oper. Res. 166*, 3 (2005), 615–648.

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MAKOWSKI, M., and WIERZBICKI, A. Modeling knowledge: Model-based decision support and soft computations. In *Applied Decision Support with Soft Computing*, X. Yu and J. Kacprzyk, Eds., vol. 124 of Series: *Studies in Fuzziness and Soft Computing*. Springer-Verlag, Berlin, New York, 2003, pp. 3–60. ISBN 3-540-02491-3.

A summary of our past activities documented in over 50 publications that characterize our experience relevant to the planned research is presented in Attachment A.

Attachment A: Past Activities

The IME Project research plan is mainly based on the research experience of Yuri Ermoliev and Marek Makowski, combined with their long-term collaboration with various IIASA programs. This research has been stimulated by the need for new methods and tools for modeling complex problems. Summarized here are selected results of that research and collaboration over the last few years.

Yuri Ermoliev has been collaborating with the Energy, Forestry and Air Pollution Programs on approaches to emission control under incomplete (asymmetric) information and interval uncertainties [20, 33]. Paper [20] deals with adaptive decentralized (bilateral and multilateral) procedures for emission charge aimed at controlling environment standards at multiple receptors under incomplete information on total costs. In contrast to the established opinion that Walrasian-type adaptive adjustments would not converge in such a case to cost-effective charges, paper [20] proves convergence. The procedures were applied to a case study for acidification in the Netherlands, and to the Aral Sea water-pricing.

A joint paper [33] with the Energy and Forestry Programs deals with GHG emission trading permits. The paper develops an adaptive sequential bilateral trade procedure with the assumption that emissions and abatement costs are known only within intervals. Such uncertainty restricts feasible trading only by verifiable emission targets, and it shows rationality for additional investments in monitoring to reduce uncertainty. The case study included countries with either major GHG emission contributions or amount of tradeable emission permits.

Paper [36] (written jointly with the Energy Program) deals with IIASA’s MESSAGE model a global energy model incorporating technological uncertainty, increasing returns, and economic, environmental, and technological risks. This work was a first attempt to combine nonconvex technological learning effects with a full-sized, global, bottom-up energy model that includes detailed regional resolution and technological representation. Computations on supercomputer T3E of US National Energy Research Computing Center examined recommendations for R&D policies, early investments in new technologies, and impact on global environment.

The long-term joint work with the LUC program and its collaborators pursues spatially explicit modeling of socio-economic and biogeophysical driving forces of land-use and land-cover change. Papers [40, 41] deal with a general approach to optimization of land-use processes in a spatial continuum by treating spatial distributions of values as probability distributions, which enables using Monte Carlo and stochastic optimizations methods. Spatial modeling requires revisions of standard spaceless economic models, in particular Walrasian-type stochastic adaptive processes developed in [18], and new approaches to estimation of econometric models proposed in [19]. Downscaling methods are needed for recovering local heterogeneities and vulnerabilities from existing aggregated data. Recently proposed sequential downscaling methods [27] are computationally efficient, which opens up possibilities to extend them for more general uncertainty and decision analysis problems.

Joint work with the RMS, LUC, and FOR programs has focused on the development of integrated approaches for coping with endogenous "unknown" (non-repetitive) catastrophic risks which may affect large territories and communities [13, 14, 15]. The main challenge is to model induced spatial and temporal heterogeneities and interdependencies among various risks, decisions, and vulnerabilities. This requires development of spatial dynamic catastrophe models (described in [14]) enabling evaluations of robust decisions via simulations in the absence of historical data. Adaptive fast Monte Carlo optimization procedures have been proposed [3, 4, 25] for integrated risk management incorporating upscaled catastrophe models developed for supporting decision-making in three catastrophe-prone areas (in Italy, Russia, and Hungary). This work required new developments in nonsmooth discontinuous stochastic optimization [14, 21] new approaches to insurability of catastrophic risks [14, 17] and long-term robust investment strategies [24, 29]. In particular, joint work [24] with the FOR program proposes new approaches to discounting long-term investments in the presence of extreme catastrophe events, where a key issue is a proper analysis of economic growth under catastrophic shocks [16].

Traditional insurance and extremal value theory deal with independent risks which can simply be pooled to guarantee their insurability. Catastrophic risks are mutually dependent (one event affects large communities and territories), therefore the traditional approaches are not fully applicable. Papers [14, 15] deal with a proper selection of interdependent fractions of risk exposures which enables insurability of the corresponding risks.

New methods and software [21, 22, 62] developed for decision problems with uncertainty aim at supporting the design of robust solutions by explicit representations of uncertainty, various risks, spatial and temporal equity constraints, potential abrupt changes, discontinuities, and rare events of high consequences. These activities essentially extend results of IIASA's program on development of numerical methods and software for stochastic systems optimization. The project was initiated in 1982 and resulted particularly in [23], which by now is a classic work on stochastic optimizations.

Marek Makowski has been working on the methods for model-based decision-making support and their applications. These collaborative activities involved several IIASA programs, and a network of researchers organized in Japan by Y. Sawaragi, and in Poland by A. Wierzbicki. The methods and tools developed at IIASA in collaboration with the network of Polish scientists have been described in [73]. M. Makowski coauthored chapters on architecture of decision support systems [58], modeling tools [67], optimization [35], interfaces [53], and software [44]. Three other chapters in [73] coauthored with colleagues from IIASA programs document the collaborative applications in air pollution [1], land use [28], and water [57]. His work on MCMA (Multicriteria Model Analysis) described e.g., in [34, 51] has not only been applied at IIASA, but the software made available on our Web-site has been taken over 2000 times (since December 1996). Our expertise in MCMA has resulted in an invitation to the NEEDS (Integrated Program of EU).

The collaboration at IIASA and with an external network has stimulated several publications, e.g., on model-based decision-support and soft computations [60], on modeling knowledge in global information networks [59, 72], on knowledge grid [48, 49], and on model-based support for policy-making and for coping with uncertainty and risk [47, 50].

In recent years modeling activities have been driven mainly by the needs of the RAINS family of models, see e.g., [1, 2, 46, 47]. Nonlinear Ozone-version of RAINS required the development of a specific problem generator coupled with pre-and post-processors, and a customized solver for badly conditioned large-scale nonlinear optimization problem. This work is partly described in [43, 45]. We have also exploited the fuzzy-rules generation methods [69] for analysis of the RAINS model results.

The time-consuming experience with developing problem specific tools for RAINS models, and the commonly known limitations of the general-purpose modeling tools (like GAMS, AMPL, AIMS) motivated us first to develop modular (reusable) tools, and second to initiate a long-term work on the Structured Modeling Technology (SMT) [52]. We have been aware of opinions that an implementation of a SMT is hardly possible, therefore its prototype was needed to demonstrate that our plans were both realistic, and relevant to modeling needs at IIASA. The SMT prototype developed in 2004 (using adapted modular modeling tools developed earlier) in collaboration with M. Majdan and C. Chudzian (both on short leaves from the National Institute of Telecommunication, Warsaw, Poland) is only partly documented in [6, 52, 63, 68]; therefore we summarize here its basic features:

- It is Web-based, which allows *anytime*, *anyplace* type of access.
- All persistent elements of the modeling process are stored in a DBMS.
- One source of model specification is used for generation of model instances, and of automatically produced documentation.
- Data Warehouse (DW) for model parameters and results of analysis is generated automatically from the model specification.
- Persistence and replicability of all modifications of model parameters (including the associated preferential structure used for model analysis) is assured by a novel mechanism of updates of the DW (which is necessary for efficient handling of modifications of large data sets). Thus it is possible to recreate the tree of modifications (and the authors and dates of modifications) of model parameters for each solution stored in the DW.
- Parametric optimization tasks are handled (generated, executed, and results stored in the DW) automatically.
- Provides automatic (but simplified) documentation of basic modeling activities.
- Supports context sensitive problem reporting.
- Handles only LP (including MIP) models.

Thus the prototype supports the entire modeling process. It has been successfully tested on the current version of RAINS (which is a medium-size LP model with a complex structure).

M. Makowski has been organizing (since 1990) annual workshops on Complex System Modeling, and several more focused workshops. He was guest co-editor of two Feature Issues of the European Journal of Operational Research [54, 56]. Two collaborative activities with Japanese partners are described in [55, 70].

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