Integrated Modeling Environment (IME) Special Project

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This document aims at providing information relevant for deciding about the IME Project extension. It is therefore composed of three main parts:
- summary of the IME background, goals and objectives,
- report of the IME activities since the Project inception in January 2006, and
- proposal for the IME 2-year (i.e., until end of 2010) extension.

1 Background, strategic goal and objectives

The IME Special Project proposal included in the IIASA 2006-2010 Research Plan was approved for 2006-2008 by the IIASA Council at its June 2005 meeting. The proposal contains the specification of the research topics, detailed discussion of the corresponding research needs and opportunities, as well as the IME contributions to IIASA objectives and mission. In this document we copy from the proposal only the IME *Strategic Goal and Objectives*, and ask the readers interested in the details to consult the full IME proposal that is available as the document COUN-65-V-d-1 submitted to the Council meeting in June 2005.

1.1 Strategic Goal and Objectives

The IME strategic goal 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 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.[3]
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.

2 IME activities

The IME objectives summarized in Section 1.1 are mutually dependent therefore IME's research can hardly be split to associate each research activity with a specific objective. The summary of IME activities is organized as follows. First we summarize in the next three Sections the research specified in the IME

[1] The Institute Scholar, and key member of the IME project.
[2] The IME Project leader.
[3] Comments of SAC on this objective are addressed in Attachment B of the IME proposal.

proposal according to the main contribution to one of the three IME objectives. In Section 2.4 we outline the research on topics not foreseen in the IME proposal, and in Section 2.5 the research by participants of the YSSP. Section 2.6 contains discussion of the problems we faced. In Sections 2.7 and 2.8 we summarize our research networks (including organized conferences) and the scientific recognition of our work, respectively. Finally, Section 2.9 contains information on the IME staff.

2.1 Advanced Web-based modeling environment

Research on the modeling environment has been composed of the two interlinked streams of activities aiming at providing Web-based environment for structured modeling and multicriteria analysis.

Structured Modeling Technology (SMT)

The SMT prototype developed by the IME provides a Web-based modeling environment supporting interdisciplinary teams during the whole modeling process (model specification, data processing, generation of model instances, and integrated model analysis). It also enables authorized users to remotely analyze the models, e.g., by modifying the data and/or objectives, and then running the optimization tasks. While the basic functionality supporting the whole modeling process has already been assured in the SMT prototype, the following two topics needed to be researched in order to effectively handle also models currently developed at IIASA:

- Analysis of semantic consistency of complex algebraic expressions. The basis for this is an effective handling of measurement units in which model components (parameters, variables, relations) are represented. The challenge of this research issue is best illustrated by the fact that analysis of consistency of measurement units is not supported by any of the widely used general purpose modeling systems. We have developed, in collaboration with researchers from the University of Ottawa, a methodological framework for this problem [64].[4]
- An efficient way for handling complex indexing structures needed for compound entities of complex models. The SMT prototype is based on professional DBMS, which provides technical possibilities of efficient handling of huge amounts of data. However, standard ways of using DBMSs are not efficient for handling data structures characterized by:
  – a huge number (over 10^9) of possible combinations of indices values, and
  – structures of indices that have to be organized into a large number of subsets that are indexed by other indices.

  IME, thanks to the collaboration with two of our former YSSPers (from the National Institute of Telecommunications, and Warsaw University of Technology, respectively) has researched data structures that can effectively manage models of complex structures and of huge sizes.

The results achieved for these two research topics provide a solid basis for a new implementation of SMT that will be capable to handle the new generation of IIASA models that: (1) are growing fast, both in complexity and in size, (2) pose new requirements for the whole modeling process, and (3) require support for remote model analysis by IIASA collaborators.

Web-based multicriteria analysis

IME also researched methods and the corresponding software technology for Web-based interactive multicriteria analysis of future energy technologies. The underlying mathematical problem is complex (in terms of number of criteria and their value distributions, and the number of discrete alternatives). Moreover, the corresponding implementation has to meet the requirements of analysis to be done by a large number (over 2000 have been invited) of stakeholders having diversified backgrounds. This research provides a basis for prototype implementation of the Web-based system currently being converted into a robust Web-based application supporting actual policy analysis within the EU-funded NEEDS project.

[4] In order to provide a clear picture of the IME work, the citations (and the corresponding bibliography) in this document are given only to the publications (co)authored by the IME staff or participants of the YSSP affiliated with the IME Project.

2.2 Coping with endogenous uncertainty and risks

Proper integrated modeling and decision analysis of on-going socio-economic and environmental global changes raise new fundamental methodological challenges. Therefore IME continues to research the key methodological issues of inherent uncertainties and risks, interdependencies, spatio-temporal (economic, social, environmental, risk exposures, political, etc.) heterogeneities that are critical elements of these processes, which have to be effectively dealt with in designing robust policy decisions. Methods for decision making under uncertainties and related issues of risk management have been at the center of world-wide methodological developments in the last couple of decades. However, these methods mainly consider the case of a relatively simple system under control facing external sources of risk and uncertainty. This, in particular, allows to separate the data and uncertainty analysis from decision analysis.

The main focus of the IME research in this area is motivated by the actual challenge of integrated modeling of global change processes: the uncertainty and risks are not only external (exogenous) to the system; they are often endogenous, generated by inappropriate policies (decisions) or/and its structural interdependencies. Designing robust decisions requires uncertainty analysis at appropriate (spatial and temporal) scales, which in turn demands advanced methods for data preparation. In order to cope with these challenges IME has advanced the development and application of new concepts of robust decisions under inherent uncertainty and risks with potential catastrophic consequences and applied them in cooperation with colleagues of several IIASA Programs. This required the development of several new models and methods. Our contributions to this development are documented by the following recent publications: [5] [6] [7] [8] [10] [13] [22] [23][40] [46] [47] [53] [55].

Here we summarize the main results:

- Jointly with the FOR and LUC Programs we developed the fundamentally new concept of endogenous spatio-temporal discounting, so-called stopping time discounting [9][48]. This approach enables evaluation of long-term spatially explicit robust risk management strategies against potentially extreme catastrophic events. The method is based on the undiscounted stopping-time criterion which is equivalent to the standard discounted criterion in the case of market-related discount factors. In general, the stopping-time criterion induces the discounting that depends on spatio-temporal patterns of catastrophes and the corresponding mitigation. Relations between such a criterion and dynamic versions of the CVaR risk measures, as well its importance for robust climate change related decisions have been studied. Important connections with the notion of Darwinian fitness were established. Applicability of discounting to a new approach to catastrophic flood management involving both structural and financial measures for the case study of the Narew river (Poland) was evaluated.
- The integrated modeling approach for robust sustainable agricultural planning under environmental and health risks was investigated and applied in case studies of livestock production expansion in China [14] [15] [18] [51]. The approach is based on specific indicators of risks that identify critical safety limitations, thresholds, and trends in locations. It essentially relies on the probabilistic downscaling methods (developed jointly with LUC Program) for supporting conversion of available multi-scale data into consistent estimates at the required (by model-based support of policy-making) scales [19] [20] [52].
- A new concept of polyhedral risk measures was studied and applied for evaluation of robust risk management investments [57]. This was done within the special project on integrated hazardous flood modeling in the Ukraine (financed by the TACIS program and coordinated by IME), in collaboration with the LUC Program, and a former YSSPer from the Glushkov's Institute of Cybernetics, the Ukraine.
- IME with FOR and LUC Programs studied an integrated modeling framework for assessing the robustness of Kyoto flexible mechanisms under uncertainties of: emissions, markets, and asymmetric information [49]. The proposed model incorporates probabilistic risk-based detection techniques with a sequential bilateral emission trading procedure in a fair and mutually beneficial way allowing to create the stable coalition of participants, and incentives to reduce involved uncertainties [17].
- Long-term research with the TNT Program was continued on methods for analyzing robust energy development under increasing returns and inherent uncertainties [12].

- In collaboration with the LUC Program we maintain long-term collaboration with our former YSSPer from the Systems Research Institute of the Polish Academy of Sciences. Recent results on integrated management of weather-related agricultural losses are presented in [50].
- Risk-based robust solutions for climate change policy have been analyzed jointly with the PCC Program [33].
- An important new concept of the so-called network risks was introduced, and studied in the context of information and social networks. This concept focuses on risks which are generated by external and internal shocks and failures inside networks of interdependent elements, such as information, energy systems or social networks [46].

2.3 Integrated model analysis

Most of the activities summarized in Sections 2.2, 2.4, and 2.5 actually support integrated model analysis. In order to avoid duplication of the information provided in these Sections we outline here only one research activity.

Building on long-term past research in the Multicriteria Model Analysis (MCMA) field the IME has been leading the activities of multicriteria analysis within the EU FP6 Integrated Project NEEDS. The overall goal of this project is to evaluate a portfolio of future energy technologies; this implies strong requirements on the research quality and transparency. In order to conform to this requirements we started our contributions with the requirement analysis [63] done in collaboration with the Paul Scherrer Institute (Switzerland). This analysis provided a basis for planning the research on new methods for the corresponding class of multicriteria analysis problems. From a mathematical point of view these are discrete alternative portfolio problems. Multicriteria analysis of discrete alternatives is widely researched, therefore many methods and corresponding tools exist. However, as analyzed in detail in [56], none of them is applicable to our application which is characterized by the following challenges:

- Multicriteria analysis is done for a large set of alternatives each characterized by a large number of criteria organized in a hierarchical structure.
- The criteria values have multimodal distributions.
- The interactive analysis process will involve many stakeholders (over 2000 will be invited) from four countries having diversified backgrounds and conflicting interests.
- The results of interactive analyses by stakeholders will provide a basis for the second stage analysis aimed at providing policy advice on future energy technologies.

There are no methods that can effectively support analysis of such problems. Therefore IME has been developing new methods for Web-based interactive multicriteria analysis which are suitable not only for this type of problems but also for several classes of "easier" problems. Initial results are summarized in [67]. The plans for further research are summarized in Section 3.2.

2.4 Research unforeseen in the research plan

Opportunities and/or needs have emerged for several research topics not identified in the research proposal prepared in 2005. We characterize here these topics, outline the justifications to engage into them, and summarize the corresponding results.

1. As a start-up IME contribution to the new IIASA cross-program initiative on *Fragility of Critical Infrastructures* IME studied novel approaches to analysis of the interdependent network risks, which are typically a combination of endogenous (generated within networks) and exogenous (outside) risks. This type of risk is the key issue defining the robustness of infrastructures, e.g., energy systems, gas, transport, and distribution systems, information and communication networks, as well as any other system of elements/activities forming a network [46] [55].

   The study of the network risks is also essential for designing robust catastrophic risk management strategies. Besides methodological issues, this research activity aimed at creation of integrated decision-making support enabling identification and evaluation of critical bottlenecks inherent in infrastructures seen as specialized networks. In particular, this is done on the example of important problems arising in the process of building the information infrastructure. It was shown how related

network risks can be analyzed by extending the portfolio theory. The Bayesian nets have been used to develop a stochastic, dynamic model of attitude formation and service adoption patterns which depend on complex interplay of attitudes of different groups of population and policies which may improve overall performance of the network.

2. Jaime Carrera-Hernández, the Colosio Fellow, joined IME in 2006 for one year to develop a decision support system for ground-water management in the Mexico-city basin. The system is based on a dedicated regional ground-water flow model. However, for making such a model operational it was necessary to first develop the hydro-geological database and to fill it with data available from diversified sources in heterogeneous formats. Actually, the most time-consuming part of the work was to collect all types of data needed for the model he developed (the data was stored in diverse institutions and formats), and to develop the database (using the open-source object-relational DBMS PostgreSQL) directly linked with the developed system of models.

   The prototype version of a decision support system for the ground-water management in the Mexico-city basin has been developed. The main challenges solved while developing this system were:
   - collecting data from different sources in diversified formats, designing a consistent and efficient data structure, and implementing the data base in PostgreSQL [1] [3],
   - data analysis [2] [4] [45],
   - development of a regional ground-water level dynamics model [41] [42] [43].
3. Hongtao Ren has researched approaches for the design of Creative Environments (CE) that support creative processes in research [35][38]. A prototype CE was developed having the following functions: creative group communication environment (posting papers, debating panels, brainstorming panels, casual knowledge sharing); electronic environment for experiment support; adaptive hermeneutic agents (help in web search; special search in texts and specialized text mining); planning and roadmapping systems [36][37]. This research was supported by 21st Century COE Program *Technology Creation Based on Knowledge and Science* of JAIST[5] funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT, Japan).
4. Motivated by needs of designing robust global change policies that require stable coalitions, IME also researched methods for analysis of a rather general risk-sharing stable coalition [40]. The analyzed approach goes beyond the concept of Pareto-optimality. Instead of the standard fixed-point arrangements, the approach entirely relies on optimization theory with its powerful computation methods. The same type of simple, direct, and computationally efficient methods have been analyzed in relation to other financial problems of pricing, portfolio selection and hedging which are typical for integrated modeling of socio-economic and environmental processes [21][53].
5. The 21st Century COE Program of JAIST financially supported our joint research in two areas of applications of the Structured Modeling Technology: (1) for knowledge integration and creation, (2) for creating virtual laboratories supporting interdisciplinary modeling. The recent results of this collaborative research are presented in [24][29][30][34].

2.5 Research by participants of the YSSP

Nine participants of the YSSP joined IME. Almost all of them achieved very good results:

- Stephan Alberth from Cambridge University researched effectiveness of learning curves for forecasting technology costs [39].
- A specific downscaling method was developed for the material flow analysis by the Shinichiro Fujimori from Kyoto University [54]. The challenge of this research was two-fold. First, the underlying problem was numerically difficult; second, due to the large number of required analyses the implementation had to be computationally efficient.
- Bayesian statistical modeling package has been developed and applied to spatial modeling of chronic diseases by Aki Havulina from the Finnish National Public Health Institute.
- Application of the Structured Modeling methodology combined with MCMA methods was adapted by Magdalena Kaska from the Warsaw University of Technology to modeling technology evolution path

[5] Japan Advanced Institute of Science and Technology, Naomi, Japan.

for development of regional Internet infrastructure.

- Search techniques for mixed-variable multi-objective optimization of stochastic systems were researched by Jennifer Walston from the US Air Force Institute of Technology [66].
- Agnieszka Banrowska (from Warsaw University of Technology, Poland) researched the insurance and capital market tools as non-structural elements of flood protection systems. The research is continued, its results are considered for new regulations in Poland, and are being applied to the Narew river in Poland.
- Aron Larsson (from Mid Sweden University) developed a framework for evaluating emergency preparedness plans and response strategies. The proposed approach is novel and promising, bridging advanced methods of decision analysis, and of ex-ante risk management. The developed method is being tested on the actual emergency preparedness plans from several Scandinavian countries [60].
- Marcin Salwa (from National Institute of Telecommunications, Poland) developed a prototype of the database for the Web-based multiuser application supporting multicriteria analysis of discrete alternatives characterized by a large number of criteria having hierarchical structure.

Moreover, the research by former YSSPers supervised by the IME staff was finalized in collaboration with the LUC Program:

- Qualitative models of climate variations impact on crops yields [58].
- Weather indicators and crop yields analysis with wavelets [59].

IME follows the proven tradition to keep contacts with former YSSPers therefore it is likely that at least some of them will collaborate with IIASA in the future.

2.6 Problems

We summarize here the main problems we faced with timely fulfillment of some tasks specified in our 2005 research proposal. We still consider the proposal to be very ambitious but realistic, and in our humble opinion we have achieved in the first 2.3 years of IME very good results. However, we have not succeeded yet to achieve the results we wanted for two activities: (1) new implementation of the SMT, and (2) integrated model analysis. There are three reasons explaining this situation.

Firstly, we have underestimated the complexity of the problems implied by the size and structure of a new generation of models developed at IIASA that we want to support through the new implementation of the SMT. Adequate support for such models cannot be achieved by incremental improvements of the SMT (that successfully supports also large and complex models). Thus, a new data structure had to be designed and implemented, and this required not only much more (than originally planned) time but also specific skills that were not readily available.

Secondly, the actual demand for our contributions to the EU Project NEEDS was much higher than originally committed, and this substantially changed the planned time budget. Formally, we could have restricted our contribution to advising on a selection of an existing multicriteria analysis method and the corresponding tool. Unfortunately, no existing method is suitable for analysis of the corresponding policy-making problem. Therefore we considered it appropriate to allocate the necessary additional resources for the development of new multicriteria methods (and the corresponding Web-based tools for interactive analysis). These new methods and tools will not only adequately support the analysis of future European energy technologies, but also provide a basis for a general purpose Web-site for multicriteria analysis of discrete alternatives. However, this unexpected need for reallocating our small human resources had caused delays in accomplishment of our other tasks.

Thirdly, securing necessary funding for a new staff member, and finding a person having appropriate qualifications took us more than one year. It is a commonly know fact that the global labor market for high quality specialists is more and more competitive, especially for researchers who combine advanced modeling experience with thorough skills in Web-based applications and professional DBMSs. Therefore in order to have a good quality research staff we do need a stable and long-term planning perspective.

Summing-up the problem's issue: we have delays in reaching some of our original goals, but we achieved good results for most of the planned research topics, and also for topics not included in our 2005 research proposal. Moreover, we have succeeded to maintain both an appropriate quality of our

research, and a rather wide spectrum of collaboration with IIASA Programs.

2.7 Research networks

The IME strategic goal is achievable only because the small in-house team is greatly supported by colleagues from: (1) collaborating IIASA Programs, and (2) the network of collaborating research institutes and universities. Therefore we summarize here our research networks, and the corresponding activities.

2.7.1 Internal collaboration

Our internal collaboration is best illustrated by the publications, most of them prepared with colleagues from IIASA Programs. Therefore here we only briefly note that our most intensive collaboration illustrated by joint publications is with the FOR and LUC Programs; joint research has also been done with the PCC and TNT Programs. Moreover, IME has intensive collaboration with the APD Program on adapting the SMT Framework to the needs of APD modeling activities (however, there are no recent joint publications yet). We have also collaborated with the DYN Program on organizing several seminars on modeling theory and practice.

IME also participated in preparation of five proposals:

- With the FOR and LUC Programs on the HUGE proposal (submitted to the ERC Advanced Grant call).
- With the LUC Program on the INFLOOD proposal (we were invited to join the consortium applying for the FP7 funding).
- With the DYN Program on the proposal on IIASA inter-program activity on the Fragility of the Critical Infrastructures.
- We prepared two proposals (one jointly with the RAV Program) in response to the IIASA IRC call for research ideas.

Finally, we have substantially contributed to activities of the Methodology Forum by co-organizing the series of seminars on scaling issues.

2.7.2 External networks

IME external collaboration includes the following institutions, with which we have various types of formal agreements:

1. EU-FP6 Integrated Program NEEDS: we lead a work-package on multicriteria analysis of future energy technologies.
2. Two Centers of Excellence (Kyoto University, and Japan Advanced Institute of Science and Technology, both Japan): agreements on collaborative research.
3. National Institute of Telecommunications, Warsaw, Poland: collaboration on the development of SMT.
4. University of Ottawa, Canada: applications of SMT for qualitative modeling.

We also maintain two collaborative networks 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 good publications and conferences. Most active participation is from:

- Germany (Federal Armed Forces University, Munich),
- 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, Trondheim; 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),
- Sweden (KTH, Stockholm),
- the Ukraine (Glushkov's Institute of Cybernetics, Kiev), and

• USA (University of California; University of Florida; Naval Postgraduate School, Monterey).

Over 30 researchers (from 8 different countries) visited IME for periods ranging from one to 15 days.

2.7.3 Workshops

IME has organized the following workshops:

• Workshop on the Requirement Analysis for Multi-criteria Methods and Tools, January 26-27 2006, IIASA (in collaboration with the Paul Scherrer Institute, Switzerland).

• SSR2006: International Symposium on Systems and Human Science: Complex Systems Approaches for Safety, Security and Reliability, March 6-8, 2006, Vienna (in collaboration with the Osaka University).

• The Third Joint International Seminar on Applied Analysis and Synthesis of Complex Systems (ASCS 2006), June 29-30 2006, IIASA (in collaboration with the COE of the Kyoto University).

• 20th Workshop on Complex Systems Modeling, August 28-30, 2006, IIASA

• Annual International Workshop on Problems of Decision-making under Uncertainty, September 2006, Kiev (in collaboration with the Taras Shevchenko National University, and the Glushkov's Institute of Cybernetics, the Ukraine).

• The Fourth Joint International Seminar on Applied Analysis and Synthesis of Complex Systems (ASCS 2007), June 28-29, 2007, IIASA (in collaboration with the COE of the Kyoto University).

• 21th Workshop on Complex Systems Modeling, August 27-29, 2007, IIASA

• Annual International Workshop on Problems of Decision-making under Uncertainty, September 2007, Kiev (in collaboration with the Taras Shevchenko National University, and the Glushkov's Institute of Cybernetics, the Ukraine).

• IFIP/IIASA/GAMM Workshop on Coping with Uncertainty (CwU): Robust Decisions, December 10-12, 2007, IIASA.

• The NEEDS project workshop, March 13-14, 2008, IIASA (in collaboration with the Paul Scherrer Institute, Switzerland).

Moreover, Yuri Ermoliev organized a special invited session on *Catastrophic Risk Management and Global Changes* at the XI International Conference of Stochastic Programming, August 2007, Vienna, Austria. Janusz Granat and Marek Makowski organized an invited session on *Multicriteria Optimization and Decision Support* at the 23rd IFIP TC-7 Conference on System Modeling and Optimization, June 2007, Krakow, Poland. Both Yuri Ermoliev and Marek Makowski have been also invited to organizing/program committees of several conferences organized by our collaborators.

2.8 Scientific recognition

We summarize here awards, editorship, selected invited lectures, and other forms of scientific recognition of the IME staff.

Yuri Ermoliev was awarded by the Ukrainian Academy of Sciences in November 2006 with the Medal for Scientific Achievements. This medal is the highest distinction of the Academy for recognition of outstanding scientific accomplishments.

Yuri Ermoliev and Marek Makowski co-edited the book *Coping with Uncertainty: Modeling and Policy Issues* published by Springer [32]. The volume presents new tools for modeling and management of uncertainty, addresses open problems, limitations of known approaches, novel methods and techniques, and lessons from applications. Moreover, Yuri Ermoliev was invited to write four articles to the *Encyclopedia of Optimization* [5] [6] [7] [8].

Janusz Granat was elected to chair the IFIP Working Group 7.6 *Optimization-Based Computer Aided Modeling* of the Technical Committee 7 *System Modeling and Optimization*.

Two IME members received their Ph.D. during their affiliation with IIASA:

• Jaime Carrera-Hernández for the dissertation on *Spatio-temporal analysis of aquifer recharge and groundwater levels in the Basin of Mexico-city* [44] defended at the McGill University, Canada.

• Hongtao Ren for the dissertation *Implementing Creative Environments for Scientific Research in a Research Institute* [65] defended at the Japan Advance Institute for Science and Technology.

Yuri Ermoliev was invited to give:

- a keynote lecture on *Using non-parametric estimation for decisions under uncertainty* at a special scientific session organized by the Glushkov Institute of Cybernetics of the Ukrainian Academy of Sciences;
- a keynote lecture on *New Methodological Challenges of System Analyses* at a special session of the International Conference on Problems of Decision Making under Uncertainties organized in cooperation with IIASA by a network of leading Ukrainian universities and institutes.

Marek Makowski was invited to deliver:

- introductory lecture on *Rational decision-making: Certain decisions in uncertain situations* at the workshop organized by the Toyota Central Research and Development Laboratories;
- plenary lecture on *Knowledge Integration and Creation for Solving Complex Problems* [61] at the Eighth International Symposium on Knowledge and Systems Sciences organized by the Japan Advanced Institute of Science and Technology;
- invited talk on *Rational Governance of Conflicting Goals, Uncertainties and Risks* [25] at the 2007 IEEE International Conference on Systems, Man, and Cybernetics;
- plenary talk on *Modeling of Large Systems Related to Environmental Problems* [62] at the 21st Conference on Informatics for Environmental Protection.

2.9 IME staff

The IME human resources are composed of:

- Current full-time in-house researchers:
  - Yuri Ermoliev, the Ukraine,
  - Marek Makowski, Poland,
  - Hongtao Ren, China (since April 2007).
- Part-time researcher: Janusz Granat, Poland (about 10% in 2006-2008, fully funded by the EU Project NEEDS).
- Part-time (75%) secretary: Amalia Priyatna, Indonesia (since August 2007).
- Former researchers:
  - Jaime Carrera-Hernández, Mexico, (Colosio Fellow, September 2006 – August 2007).
  - Cezary Chudzian, Poland, (Mikhalevich Scholarship Award, one month in 2006).
  - Sjur Flaam, Norway, one month in 2007,
  - Alexei Gaivoronski, Norway, six weeks in 2007.
  - Bartosz Kozłowski, Poland, (Mikhalevich Scholarship Award, five months in 2006).

3 Proposal for the IME extension until end of 2010

The IME proposal was prepared in 2005 for the whole period of the IIASA 2006-2010 research plan with assumption that a positive evaluation of the IME achievements and its role in IIASA research portfolio would provide a basis for the Council decision about extension of the IME Project until the end of the current IIASA research period. Therefore in this Section we first compile arguments supporting a positive evaluation of the IME Project, and then summarize plans for future research activities.

3.1 Assessment by the Evaluation Committee

Instead of attempting a subjective self-evaluation of our activities we copy (in *italics font* below) the text of the IME assessment included in the report of the Evaluation Committee on the IIASA Theme *Population and Society*.[6] The report provides an objective assessment of not only quality of our research but also of the IME role in the IIASA research.

[6]The Committee report submitted to the June 2007 IIASA Council meeting is available as the Council document COUN-69-V-e-1.

The IME, along with DYN, appear to be IIASA's last vestiges of "Applied System Analysis" with an emphasis placed on methodological development. This comment is reflected in the IME self-study report and their future plans stating that an objective of IME 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."

With the thrust of IIASA toward more applied directions, a natural question is to determine the role played by IME. After all, as we learned during our visit, other IIASA projects have developed strong, discipline-specific expertise in the modeling of their specific concerns. As an example, part of the excellent reputation enjoyed by POP group derives from their creation of new and innovative approaches to handle population forecasts.

It is clear that if the different IIASA programs are to remain on the cutting edge of research, their models must become more sophisticated. This means these models will be, and are becoming, larger, more complex, with the need to incorporate more interacting factors and variables. Accompanying the development of new models are methodological challenges, which cut across projects, that tend to involve discovering ways to generate and analyze complex models and to create a Web-based modeling environment. This similarity of needs suggests that rather than each group trying to develop their own expertise in these areas, a IIASA strategy that would lead to faster and sharper results on a more cost efficient basis is to develop general expertise on these methodological topics. This is the purpose of IME.

The committee's evaluation of IME was based on this interpretation of their role within IIASA. All evidence we found underscored the excellence of the research and the contributions being made to other projects by the IME group. This assessment is based on comments made by the anonymous reviewers, the self-study, and our discussions with IME representatives. The contributions that IME makes to other IIASA projects appears to be well recognized and appreciated within the institute; an example is the work of the IME personnel on the RAINS model. Moreover, as the external reviewers mentioned, recognition of IME research contributions by the research community outside of IIASA appears to be strong.

These positive comments are further manifested by the research network that IME has created with researchers in Japan and Poland, the 2000 downloads of software they made available on their webpage, their publications, their success in external funding, and their strong success with YSSP participants. From what we were able to determine, their many accomplishments, summarized starting on the bottom of page 4 to the top of page 5 of their self-evaluation report, provide an accurate view of their success. This is a strong, valued group for IIASA.

In our opinion the above assessment provides strong arguments for deciding about the IME project extension. We also agree[7] with more general (i.e., not IME specific) comments and recommendations of the Evaluation Committee. Our motivation has been (and will continue to be) to address as many needs for novel methodology as possible with available resources while assuring quality of research. Therefore we continue to look for more resources needed for effectively addressing possibly many IIASA needs for novel and effective modeling methods and tools. We have succeeded to acquire substantial amount of external funding without taking risks of making our research driven by that funding. However, conforming to this principle combined with the limitations of the IIASA budget also constraints the scope of the IME research.

3.2 Future research priorities

We continue to base our activities on the research proposal submitted to the Council in 2005. This research proposal defines a research scope within which we select activities that fit best to the current needs of collaborating IIASA Programs and external collaborators. Considering these needs and the available external funding the following research topics will have priority in near future:

- A new generation of the SMT-based modeling environment tuned to the needs of the collaborating IIASA Programs.

[7] Our comments to the report of the Evaluation Committee are available on pages 7-11 of the *Director's and Program Leader's Response to Report of the Evaluation Committee on Population and Society* (document COUN-69-V-e-2 submitted to the June 2007 Council meeting).

- Further advancement of research aimed at designing model-based robust policy-making decisions, focused on the selected problems of inherent uncertainties and interdependent endogenous risks, including:
  – spatio-temporal discounting,
  – increasing returns, especially in the context of robust energy technology development,
  – downscaling/upscaling, especially in the context of spatio-temporal modeling,
  – safety of integrated systems,
  – assessment of Kyoto-Protocol flexible mechanisms.
- The Web-based multicriteria analysis of future energy technologies (to be done by a large number of stakeholders invited by the coordinator of the EU-funded NEEDS project).
- Development of new data analysis methods aimed at finding a portfolio of future energy technologies (out of the set of technologies developed by the EU Project NEEDS) that correspond best to the stakeholder preferences implicitly specified during the multicriteria analysis performed by a large number of stakeholders.
- Develop a general purpose Web-site for multicriteria analysis of discrete alternatives (this will be a spin-off of the activities contributed to the EU Project NEEDS).

The following recently submitted publications characterize some of the current research activities: [11] [16] [17] [26] [27] [28] [31].

Contingent on additional/external funding/resources also the following topics will be further researched:

- The network risks in the context of robustness of critical infrastructures, e.g., energy systems, gas, transport, communication, and distribution systems, information and social networks (within the forthcoming IIASA inter-program activity on *Fragility of Critical Infrastructures*).
- Increasing environmental effectiveness of a Post-Kyoto Agreement. Proposal submitted for the ERC Advanced Grant by FOR, IME and LUC.
- Integrated management of catastrophic flush floods risks. Proposal submitted to the FP7 by the INFLOOD consortium (invited IIASA participants: IME and LUC).
- Pricing of catastrophe bonds and options focused on applications to integrated management of risks related to natural disasters (in collaboration with the LUC Program). Depends on the pending application of a Ph.D. student to the China Scholarship Council.
- The insurance and capital market tools as non-structural elements of flood protection systems, and its application to the Narew river (Poland) case study.

4 Concluding remarks

Based on our experience we believe that complex practical problems that cannot be adequately solved by established methods are the best drivers for development of novel methodology, and we think that our achievements illustrate this. IIASA's strength comes from the synergy of abilities to:

- develop novel methods for integrated multidisciplinary models that are appreciated as leading in disciplinary communities (including mathematics, operational research, economics), and
- actually apply them in cooperation with IIASA scientists having a strong reputation in their substantive domains (including air pollution, energy, forestry, land-use).

The latter guarantees that the strong interdisciplinary science is actually utilized for policy-making support; the former assures that the methods used are indeed the best available not only in the substantive domains but also in applied mathematics.

5 IME Publications 2006–2008

5.1 Peer-reviewed publications

[1] J.J. Carrera-Hernández and S.J. Gaskin. The Basin of Mexico aquifer system: Regional groundwater table dynamics and database development. *Journal of Hydrogeology*, pages 1577–1590, 2007.

[2] J.J. Carrera-Hernández and S.J. Gaskin. Spatio temporal analysis of daily precipitation and temperature in the Basin of Mexico. *Journal of Hydrogeology*, pages 231–249, 2007.

[3] J.J. Carrera-Hernández and S.J. Gaskin. The Basin of Mexico hydrogeological database. *Journal Hydrogeology*, 2008.

[4] J.J. Carrera-Hernández and S.J. Gaskin. Spatio-temporal analysis of potential aquifer recharge. *Journal of Hydrogeology*, 2008.

[5] Y. Ermoliev. Stochastic quasgradient methods in minimax problems. In C.A. Floudas and P.M. Pardalos, editors, *Encyclopedia of Optimization*. Springer, Berlin, Germany, 2008. ISBN 978-0-387-74758-3.

[6] Y. Ermoliev. Stochastic quasigradient methods. In C.A. Floudas and P.M. Pardalos, editors, *Encyclopedia of Optimization*. Springer, Berlin, Germany, 2008. ISBN 978-0-387-74758-3.

[7] Y. Ermoliev. Stochastic quasigradient methods: Applications. In C.A. Floudas and P.M. Pardalos, editors, *Encyclopedia of Optimization*. Springer, Berlin, Germany, 2008. ISBN 978-0-387-74758-3.

[8] Y. Ermoliev. Two-stage stochastic programming: Quasigradient method. In C.A. Floudas and P.M. Pardalos, editors, *Encyclopedia of Optimization*. Springer, Berlin, Germany, 2008. ISBN 978-0-387-74758-3.

[9] Y. Ermoliev, T. Ermolieva, G. Fischer, M. Makowski, S. Nilsson, and M. Obersteiner. Discounting, catastrophic risks management and vulnerability modeling. *Mathematics and Computers in Simulation*, 2008. (in press).

[10] Y. Ermoliev, T. Ermolieva, and V. Norkin. Economic growth under shocks: Path dependencies and stabilization. In H. Liljenstroem and U. Svedin, editors, *Addressing Complex Systems Couplings*, pages 289–302. World Scientific Publishing Co. Pte. Ltd, Singapore, 2006.

[11] Y. Ermoliev, A. Gaivoronski, and M. Makowski. Robust design of networks under risks. In K. Marti, Y. Ermoliev, and M. Makowski, editors, *Coping with Uncertainty: Robust Decisions*. Springer, Berlin, Germany, 2008. forthcoming.

[12] Y. Ermoliev, A. Gritsevskyi, and A. Grübler. Modeling robust technological developments under increasing returns and uncertainties. In K. Marti, Y. Ermoliev, and M. Makowski, editors, *Coping with Uncertainty: Robust Decisions*. Springer, Berlin, Germany, 2008. forthcoming.

[13] Y. Ermoliev and L. Hordijk. Facets of robust decisions. In *Coping with Uncertainty: Modeling and Policy Issues*, pages 3–28. Springer, Berlin, Heidelberg, New York, 2006.

[14] T. Ermolieva, Y. Ermoliev, G. Fischer, and M. Makowski. Catastrophic risks, vulnerability, and land use. In C. Huang, C. Frey, and J. Feng, editors, *Integrated Risk Management Approaches for Planning Sustainable Agriculture*. Atlantis Press, Paris, 2007. ISBN 978-90-78677-03-1.

[15] T. Ermolieva, Y. Ermoliev, G. Fischer, and L. Sun. Integrated risk management approaches for planning sustainable agriculture. In C. Huang, C. Frey, and J. Feng, editors, *Catastrophic Risks, Vulnerability, and Land Use*. Atlantis Press, Paris, 2007. ISBN 978-90-78677-03-1.

[16] T. Ermolieva, Y. Ermoliev, M. Makowski, and G. Fischer. Endogenous discounting and catastrophic risks. In K. Marti, Y. Ermoliev, and M. Makowski, editors, *Coping with Uncertainty: Robust Decisions*. Springer, Berlin, Germany, 2008. forthcoming.

[17] T. Ermolieva, M. Jonas, Y. Ermoliev, M. Makowski, and G. Fischer. Robust and efficient dynamic bilateral emission trading under uncertainties. In K. Marti, Y. Ermoliev, and M. Makowski, editors, *Coping with Uncertainty: Robust Decisions*. Springer, Berlin, Germany, 2008. forthcoming.

[18] G. Fischer, T. Ermolieva, Y. Ermoliev, and H. van Velthuizen. Livestock production planning under environmental risks and uncertainties. *Journal of Systems Science and Systems Engineering*, 14(4), 2006.

[19] G. Fischer, T. Ermolieva, Y. Ermoliev, and H. van Velthuizen. Sequential downscaling methods for estimation from aggregate data. In K. Marti, Y. Ermoliev, M. Makowski, and G. Pflug, editors, *Coping with Uncertainty, Modeling and Policy Issues*. Springer Verlag, Berlin, Germany, 2006.

[20] G. Fischer, T. Ermolieva, Y. Ermoliev, and H. van Velthuizen. Spatial recovering of agricultural values from aggregate information: Sequential downscaling methods. *International Journal of Knowledge and Systems Sciences*, 2006.

[21] S. Flaam and Y. Ermoliev. Investment, uncertainty, and production games. *Environment and Development Economics*, 2008. (accepted).

[22] M. Keyzer, Y. Ermoliev, and V. Norkin. General equilibrium models with discreet choices in a spatial continuum. In K. Marti, Y. Ermoliev, M. Makowski, and G. Pflug, editors, *Coping with Uncertainty, Modeling and Policy Issues*, pages 133–153. Springer-Verlag, Berlin, Germany, 2006.

[23] M. Makowski. Structured modeling for coping with uncertainty in complex problems. In K. Marti, Y. Ermoliev, M. Makowski, and G. Pflug, editors, *Coping with Uncertainty: Modeling and Policy Issues*, pages 47–64. Springer, Berlin, Heidelberg, New York, 2006.

[24] M. Makowski. Knowledge integration and creation for solving complex problems. *International Journal of Knowledge and Systems Sciences*, 4(3):26–32, 2007. ISSN 1349-7030.

[25] M. Makowski. Rational governance of conflicting goals, uncertainties and risks. In *Proceedings of the 2007 IEEE International Conference on Systems, Man, and Cybernetics*, pages 1812–1817. IEEE, Omnipress, Montreal, Canada, 2007. ISBN 1-4244-0991-8.

[26] M. Makowski. Advances in modeling methodology for supporting environmental policymaking. *Archives of Environmental Protection*, 2008. invited paper, submitted.

[27] M. Makowski. Management of tradeoffs between conflicting goals. *Journal of Computers*, 2008. ISSN1796-203X; invited paper, submitted.

[28] M. Makowski. SMT: a service-based environment for model sharing. In D. Dolk and J. Granat, editors, *Modeling and Decision Support for Network-based Services*, Lecture Notes in Business Information Processing. Springer, Berlin, Heidelberg, New York, 2008. ISSN-1865-1348, forthcoming.

[29] M. Makowski, Y. Nakamori, and A. Wierzbicki. Decision support versus knowledge creation support. In A. Wierzbicki and Y. Nakamori, editors, *Creative Space: Models of Creative Processes for Knowledge Civilization Age*, volume 10 of *Series: Studies in Computational Intelligence*, pages 219–250. Springer, Berlin, Heidelberg, New York, 2006. ISBN 3-540-28458-3.

[30] M. Makowski and A. Wierzbicki. Virtual laboratories. In A. Wierzbicki and Y. Nakamori, editors, *Creative Environments: Issues of Creativity Support for Knowledge Civilization Age*, volume 59 of *Series: Studies in Computational Intelligence*, pages 233–254. Springer, Berlin, Heidelberg, New York, 2007. ISBN 978-3-540-71466-8.

[31] K. Marti, Y. Ermoliev, and M. Makowski, editors. *Coping with Uncertainty: Robust Decisions*. Lecture Notes in Economics and Mathematical Systems. Springer, Berlin, Heidelberg, New York, 2008. forthcoming.

[32] K. Marti, Y. Ermoliev, M. Makowski, and G. Pflug, editors. *Coping with Uncertainty: Modeling and Policy Issues*, volume 581 of *Lecture Notes in Economics and Mathematical Systems*. Springer, Berlin, Heidelberg, New York, 2006. ISBN 978-3-540-35258-7.

[33] B. O'Neill, Y. Ermoliev, and T. Ermolieva. Endogenous risks and learning in climate change decision analysis. In K. Marti, Y. Ermoliev, M. Makowski, and G. Pflug, editors, *Coping with Uncertainty, Modeling and Policy Issues*. Springer Verlag, Berlin, Germany, 2006.

[34] W. Purwasih, M. Makowski, Y. Nakamori, and T. Yoshida. Documenting a model structure by diagram. *International Journal of Knowledge and Systems Sciences*, 3(4):60–67, 2006. ISSN 1349-7030.

[35] H.T. Ren, J. Tian, Y. Nakamori, and A.P. Wierzbicki. Creative environments for scientific research in a research institute. *International Journal of Knowledge and Systems Sciences*, 4(2), 2007.

[36] H.T. Ren, J. Tian, Y. Nakamori, and A.P. Wierzbicki. Electronic support for knowledge creation in a research institute. *The Journal of System Science and System Engineering*, 16(2), 2007.

[37] J. Tian, Y. Nakamori, H.T. Ren, and A.P. Wierzbicki. Testing the triple helix model. In A.P. Wierzbicki and Y. Nakamori, editors, *Creative Environments: Issues of Basic of Creative Processes*, volume 9. Springer and Heidelberg, Berlin and New York, 2007. ISBN 978-3-540-71466-8.

[38] A.P. Wierzbicki and H.T. Ren. Integrated support for scientific creativity. In A.P. Wierzbicki and Y. Nakamori, editors, *Creative Environments: Issues of Basic of Creative Processes*, volume 9. Springer and Heidelberg, Berlin and New York, 2007. ISBN 978-3-540-71466-8.

5.2 Reports, contributions to proceedings, Ph.D. thesis

[39] S. Alberth. Forecasting technology costs via the learning curve-myth or magic. Interim Report IR-06-058, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006.

[40] A. Borglin and S.D. Flaam. Risk exchange as a market or production game. Interim Report IR-07-033, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[41] J.J. Carrera-Hernández and S.J. Gaskin. Spatio temporal distribution of potential aquifer recharge in the Basin of Mexico. In *MODFLOW and MORE 2006: Managing Groundwater Systems*, Golden, Colorado, USA, May 2006.

[42] J.J. Carrera-Hernández and S.J. Gaskin. Spatial dynamics of aquifer recharge in the Basin of Mexico. In *IAHR Conference:Harmonizing the Demands of Art and Nature in Hydraulics*, Venice, Italy, July 2007.

[43] J.J. Carerra-Hernández. The Basin of Mexico hydrogeological database. Interim Report IR-07-018, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[44] J.J. Carrera-Hernández. *Spatio-temporal analysis of aquifer recharge and groundwater potentiometric levels in the Basin of Mexico through the development of a regional database and an open source tool for groundwater flow modeling*. PhD thesis, Mc.Gill University, Montreal, Canada, 2007.

[45] J.J. Carrera-Hernández and S.J. Gaskin. A regional hydrogeological model for the Basin of Mexico. In *Geophysical Research Abstract*, Vienna, Austria, April 2007. European Geosciences Union General Assembly.

[46] Y. Ermoliev, A. Gaivoronski, and M. Makowski. Modeling and robust design of networks under risk: the case of information infrastructure. Interim Report IR-07-39, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[47] Y. Ermoliev and L. Hordijk. Global changes: Facets of robust decisions. Interim Report IR-06-001, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006.

[48] T. Ermolieva, Y. Ermoliev, G. Fischer, and M. Makowski. Induced discounting and risk management. Interim Report IR-07-40, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[49] T. Ermolieva, M. Jonas, and M. Makowski. The difference between deterministic and probabilistic detection of emission changes: Toward the use of the probabilistic verification time concept. In *Proc. of the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories, IIASA*, Systems Research Institute of the Polish Academy of Sciences, September 2007.

[50] T. Ermolieva, M. Romaniuk, and M. Makowski. Integrated model-based decision support for management of weather-related agricultural losses. In *Proceedings of 21st Conference on Informatics for Environmental Protection*, Warsaw, Poland, 2007. Systems Research Institute of the Polish Academy of Sciences.

[51] G. Fischer, T. Ermolieva, and Y. Ermoliev. Land use, vulnerability and catastrophe. In *International Symposium on Systems and Human Science*, 2006.

[52] G. Fischer, T. Ermolieva, Y. Ermoliev, and H. van Velthuizen. Sequential downscaling method from aggregate data. Interim Report IR-06-002, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006.

[53] S.D. Flaam. Option pricing by mathematical programming. Interim Report IR-07-032, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[54] S. Fujimori. A new practical method for estimation of input-output tables. Interim Report IR-07-015, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[55] A. Gaivoronski and A. Werner. Modeling of competition and collaboration networks under uncertainty: stochastic programs with resource and bilevel structure. Interim Report IR-07-041, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[56] J. Granat and M. Makowski. Multicriteria methodology for the NEEDS project. Technical report, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006. (report for the EU Project NEEDS; restricted distribution).

[57] V. Kirilyuk. Polyhedral coherent risk measures, portfolio optimization and investment allocation problems. Interim Report IR-07-030, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[58] W. Kotłowski. Qualitative models of climate variations impact on crops yields. Interim Report IR-07-034, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[59] B. Kozłowski. Weather indicators and crop yields analysis with wavelets. Interim Report IR-07-038, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[60] A. Larsson. A framework for evaluating emergency preparedness plans and response strategies. Interim Report IR-08-008, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2008.

[61] M. Makowski. Knowledge integration and creation for solving complex problems. In Y. Nakamori, Z. Wang, J. Gu, and T. Ma, editors, *Proceedings of the Eighth International Symposium on Knowledge and Systems Sciences*, pages 27–34. JAIST Press, Nomi, Ishikawa, Japan, 2007. ISBN 978-4-903092-07-2.

[62] M. Makowski. Modeling of large systems related to environmental problems. In *Proceedings of 21st Conference on Informatics for Environmental Protection*, Warsaw, Poland, 2007. Systems Research Institute of the Polish Academy of Sciences.

[63] M. Makowski, J. Granat, W. Schenler, and S. Hirschberg. Requirement analysis for WP9 of NEEDS RS2b. Technical report, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006. (report for the EU Project NEEDS; restricted distribution).

[64] V. Nastase, M. Makowski, and W. Michalowski. Dimensional consistency analysis in complex algebraic models. Interim Report IR-07-29, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[65] H.T. Ren. *Implementing Creative Environments for Scientific Research in a Research Institute*. PhD thesis, Japan Advanced Institute of Science and System Engineering, Japan, 2007.

[66] J.G. Walston. Search techniques for multi-objective optimization of mixed-variable systems. Interim Report IR-07-014, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.

[67] A. Wierzbicki, J. Granat, and M. Makowski. Discrete decision problems with large number of criteria. Interim Report IR-07-25, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2007.