International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Requirement Analysis and Implementation of Multicriteria Analysis in the NEEDS Project

Makowski, M., Granat, J., Ren, H., Schenler, W. and Hirschberg, S.

IIASA Interim Report
November 2009

International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-09-09

Requirement Analysis and Implementation of Multicriteria Analysis in the NEEDS Project

Marek Makowski (marek@iiasa.ac.at)
Janusz Granat (J.Granat@itl.waw.pl)
Hongtao Ren (renh@iiasa.ac.at)
Warren Schenler (Warren.Schenler@psi.ch)
Stefan Hirschberg (Stefan.Hirschberg@psi.ch)

Approved by

Detlof von Winterfeldt (detlof@iiasa.ac.at)
Director, IIASA

November 2009

Foreword

Public participation in decision-making is almost always desired but difficult to effectively achieve, especially in situations where the decision problem is complex and a policy recommendation requires involving large and diversified groups of stakeholders. Making recommendations for European future energy technologies is an example of such a problem. Its analysis implicitly defines a class of multicriteria analysis problems composed of large sets of alternatives, each characterized by a large number of criteria organized in a hierarchical structure. These criteria are diverse and conflicting, and are organized into three sets composed of economic, environmental, and social criteria respectively. Each of these sets has the hierarchical structure of the corresponding criteria. Moreover, the stakeholders invited to make the analysis not only had different preferences for trade-offs between such criteria, but also diversified backgrounds and thus typically very limited experience in analyzing problems using formal multicriteria approaches, and especially in defining preferences.

There existed neither suitable methods nor tools to support multicriteria analysis of such a problem. Therefore the team that both developed the methods and implemented them as a dedicated Web-site had to solve a number of methodological and technological challenges. This report first describes the requirement analysis for the corresponding class of problems, and then summarizes the implementation of the tool used for interactive multicriteria analysis of future energy technologies by the large and diversified group of stakeholders.

The lessons learned from the documented process are of interest to both researchers and practitioners involved in development of methods and/or tools for multicriteria analysis, especially of large sets of discrete alternatives.

Abstract

This report specifies the requirements for and implementation of the multicriteria analysis of future energy technologies performed by a large number of stakeholders within the EU-funded integrated project NEEDS. The report is composed of two main parts and the appendix.

The first part starts with a summary of the objectives of the analysis followed by a detailed specification of the analyzed problem, in particular the analysis context, discussion of the sets of criteria and alternatives, and the participation of the stakeholders. Next, the planned problem analysis process is first outlined, and then discussed in more detail. Finally, the requirements for the multicriteria analysis are specified.

The second part deals with the implementation of the dedicated Web-site developed for this analysis, and later extended to support analysis of any multicriteria choice between discrete alternatives. It starts with an overview of the problem analysis process and the corresponding basic assumptions. The architecture of the application and its features are then presented. Lessons learned from the development and use of this application conclude this part of the report.

The appendix contains a review of the state-of-the-art of applying multicriteria analysis to energy problems, as well as characteristics of three applications that exploit the multicriteria analysis methods for energy problems considered relevant to the analysis reported in this paper.

Acknowledgments

The authors gratefully acknowledge help of Bartosz Kozłowski of IIASA, who over the period of four years has systematically contributed his expertise in several areas, including data basis, Web-based applications, and software development. Moreover, he has provided the so-called *Framework* composed of software modules supporting implementation of Web-based applications.

The authors also thank colleagues from the Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Villigen, Switzerland for their comments and suggestions. We especially thank Peter Burgherr for his numerous comments on the MCA design and implementation, as well as for contributions to the preparations and running the analysis. We also thankfully acknowledge the comments of members of other teams participating in the Research Stream 2b of the NEEDS project provided during testing of the application described in this report.

The research reported in this paper was partly financially supported by the EC-funded Integrated Project NEEDS (project no: 502687), and by the Austrian Federal Ministry of Science and Research.

About the authors

Marek Makowski leads the IIASA Integrated Modeling Environment Project. His research interests focus on model-based support for solving complex problems, which incorporates three interlinked areas. First, integration of interdisciplinary knowledge and its representation by mathematical models. Second, creation of knowledge by comprehensive model analysis, including multicriteria methods. Third, tailoring the modeling process to meet the needs of decision-making processes. Thus Marek's research interests cover a cluster of areas relevant to the adaptation (whenever possible) or development (when needed) of methodology, algorithms, and software for model-based decision-making support. This includes more specific topics in Operations Research such as: multicriteria problem analysis, large scale optimization, optimization of badly conditioned problems, use of database management systems for complex models, decision analysis and support, user interfaces in decision support systems, effective treatment of uncertainty and risk.

Marek has published over 130 papers and book-chapters, co-edited four books, coordinated or led several scientific projects, and has been twice guest editor of the European Journal of Operational Research.

Janusz Granat is a leader of the Division of Advanced Information Technology at the National Institute of Telecommunications. He also lectures on decision support systems and management information systems at the Warsaw University of Technology. His scientific interests include decision support systems, multi-criteria analysis, modeling, data mining, event mining, techno-economic analysis and the design of the telecommunications network. He has been involved in various industrial and scientific projects e.g., data warehousing and decision support systems for telecommunication industry, building data mining models for marketing departments, development of decision support systems for energy management.

Hongtao Ren is a researcher in the IIASA Integrated Modeling Environment Project (IME). His research interests include modeling environments, computerized support for knowledge creation, integrated systems for scientific creativity, knowledge engineering, the semantic web, and text mining. He has developed diverse Web-based applications in collaboration with IIASA colleagues, including Multiple Criteria Analysis of Discrete Alternatives, and Multiple Criteria Analysis of Future Energy Technologies. He has participated in various activities of the Center of Excellence at the Japan Advanced Institute of Science and Technology, and in particular has developed Creative Environments for supporting scientific research.

Warren Schenler is a researcher in the Interdepartmental Laboratory for Energy Systems Analysis at the Paul Scherrer Institute (PSI), Switzerland. He has worked on energy research projects, and especially on electric power system research issues, related to the United States, Switzerland, Germany, the EU and China. His core interests include system and technology interactions, including sector and societal economics, system operation and risk, and social impacts like employment. He has experience in applying multicriteria decision analysis to questions of energy and sustainability, including the design of sustainability criteria sets, multi-scenario simulation and data mining. Other interests include the interaction between the electric power sector and other energy sectors such as hydrogen and transportation.

Stefan Hirschberg is the head of the Interdepartmental Laboratory for Energy Systems Analysis at the Paul Scherrer Institute (PSI), Switzerland. The Laboratory consists of three Groups: Technology Assessment, Energy Economics, and Risk and Human Reliability. Since 1992 he has been coordinating interdisciplinary activities on ”Comprehensive Assessment of Energy Systems”. He manages a number of projects for energy and environmental authorities, for electrical utilities and vendors, and within international programs. His main research interests currently include: Life Cycle Assessment, Environmental Impact and External Cost Assessment, Comparative Risk Assessment, Sustainability Assessment and Development of Integrated Tools for Decision Support. Stefan has about 200 publications and lectures at the Swiss Federal Institutes of Technology in Zurich and Lausanne. He has been a member of numerous advisory, consultant and expert groups supporting national and international organizations. In 2008 Stefan was elected an individual member of the Swiss Academy of Engineering Sciences (SATW). Before joining PSI he was responsible for Risk and Reliability Assessment within ABB, Sweden and during a leave of absence for Probabilistic Safety Assessment at the IAEA.

Contents

List of Tables

List of Figures

Requirement Analysis and Implementation of Multicriteria Analysis in the NEEDS Project

Marek Makowski[*] *(marek@iiasa.ac.at)*
Janusz Granat[** ***] *(J.Granat@itl.waw.pl)*
Hongtao Ren[*] *(renh@iiasa.ac.at)*
Warren Schenler[****] *(Warren.Schenler@psi.ch)*
Stefan Hirschberg[****] *(Stefan.Hirschberg@psi.ch)*

1 Introduction

The purpose of this report is to provide an analysis of requirements for a fairly complex process of multicriteria analysis of European future energy technologies done by a large number of diversified stakeholders, and to summarize how these requirements were actually met by implementing a dedicated Web site combined with a suite of supporting applications. The activities described in this report were done within the EU-funded project NEEDS *"New Energy Externalities Developments for Sustainability"*.[1] The requirements presented here show the complexity of the process, and the corresponding research and technological challenges. Therefore the lessons from the approach to public participation described in this paper are of interest of researchers and practitioners involved in science-based support for policy making.

The MCA-Needs has been developed within the Research Stream 2b (RS2b) of the NEEDS project, and was thus a part of a fairly large research activity, which in turn was a component of a very large integrated project in which over 70 institutions took part. The general objectives of the RS2b were:

1. To identify, discuss and analyze the terms and conditions for an effective formulation and implementation of long term energy strategies.

2. To broaden the basis for decision support beyond the assessment of external costs by examining the robustness of results under various stake-holder perspectives.

3. To contribute to the integration of results by other analytical tasks with the NEEDS project.

[*] Integrated Modeling Environment Project, IIASA.
[**] National Institute of Telecommunications, Warsaw, Poland.
[***] Warsaw University of Technology, Warsaw, Poland.
[****] Paul Scherrer Institut, Villigen, Switzerland.
[1] The documentation of the NEEDS project is available at `http://www.needs-project.org`.

The specific objectives relevant to the development of MCA-Needs were:

1. To evaluate energy technologies and scenarios taking into account diverse preferences of a large group of stakeholders for trade-offs between economic, environmental, and social criteria characterizing the technologies.

2. To investigate the sensitivity of the results of sustainability assessment to specific patterns in stake-holder preferences.

Multi-criteria analysis was therefore a key element of the RS2b research and the resulting policy recommendations. The original plan was to select a MCDA (Multi-Criteria Decision Analysis) approach and software best suited for the purpose of NEEDS. When making this choice, the arrangement of interactions with stakeholders needed to be taken into account. The original report [13] provided a basis for the report [5], which in turn justified the need for development of new methods for multicriteria analysis of the corresponding class of discrete alternative problems, and a new Web-based tool enabling such an analysis. An updated version of [5] is available as [6], which also provides information about the new MCDA methods developed and implemented first for the NEEDS project, and later extended for a multicriteria analysis of any problem of discrete choice.

Analyses of European future energy technologies implicitly defined a class of multi-criteria analysis problems composed of large sets of alternatives, each characterized by a large number of criteria organized in a hierarchical structure. The criteria are diversified and conflicting, and are organized into three sets composed of economic, environmental, and social criteria respectively. Each of these sets has the hierarchical structure of the corresponding criteria. Moreover, the analysis has been done by different stakeholders who not only have different preferences for trade-offs between such criteria, but also diversified backgrounds and thus typically very limited experience in analyzing problems using formal multicriteria approaches, and especially in defining preferences. Therefore suitable MCDA methods and corresponding modeling tools were necessary for reaching the key objectives of the RS2b.

This report is composed of the selected (and updated) elements of the original *Requirement Analysis* [13] and new parts that summarize the implementation of the dedicated Web-based application (here called MCA-Needs) developed for meeting the requirements of multicriteria analysis of future energy technologies done by the stakeholders invited by the EU-funded NEEDS project.

The report is composed of two main parts:

- a requirement analysis for the MCA-Needs, and
- a summary of the MCA-Needs implementation and lessons from its actual use.

We now summarize the structure of these two main parts.

Content and structure of the requirement analysis: This part of the report is organized as follows: Section 2 provides a detailed specification of the problem to be subjected to multicriteria analysis; this includes the summary of the analysis context, discussion of the sets of criteria and alternatives, and the participation of the stakeholders. The implemented problem analysis process is summarized in Section 3. Section 4 specifies the requirements for multicriteria analysis; it is composed of two parts: (1) the user perspective, and (2) infrastructure and organization. In addition, the Appendix contains the characteristics of three energy applications that exploit different multicriteria analysis methods pertinent to the multicriteria analysis in NEEDS RS2b.

Implementation and experience: Section 5 summarizes the basic assumptions adopted for the implementation, and the key features of the dedicated Web-based application for the multicriteria analysis called MCA-Needs, its architecture and description of its implementation. The lessons learned from implementation and use of the MCA-Needs are provided in Section 6.

Additionally, the appendix contains a review of the state-of-the-art of applying multicriteria analysis to energy problems, as well as characteristics of three applications that exploit different multicriteria analysis methods for energy problems considered relevant to the analysis reported in this paper.

2 Problem specification

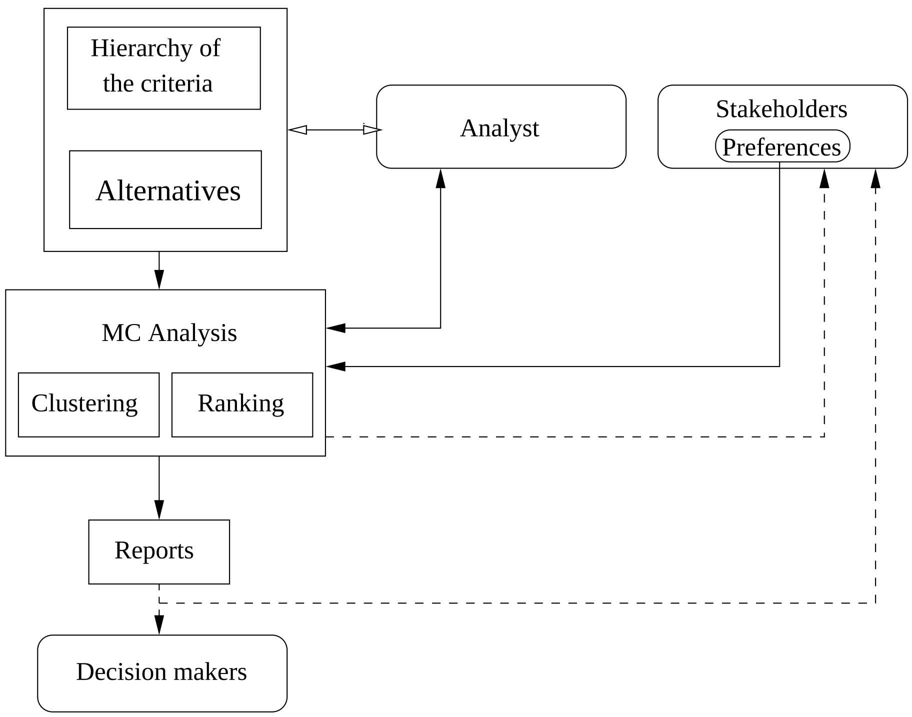

Figure 1: General structure of the problem analysis process.

This Section starts with a top-level summary of the class of problems for which the MCA-Needs has been developed.[2] The general structure of the problem analysis process is illustrated in Figure 1 and is characterized as follows:[3]

[2]The context of such an analysis is summarized in Section 2.1.

[3]The characteristics provided here differs slightly from those included in the original requirement analysis [13] because the latter had to be adjusted to the actual developments in the NEEDS project.

1. A set of approximately 60 criteria is given, organized in a hierarchical structure of up to 4 levels. Two types of criteria are distinguished:
   - Indicators (also called attributes), i.e., the criteria for which values were determined for each alternative. Indicators are therefore included into the hierarchical criteria as the leaf-criteria.
   - Higher[4]-level criteria. The higher-level criteria have no physical values; they only serve for specifying multiplicative preference in the criteria tree. There are three highest-level criteria, each corresponding to one of the three sustainability pillars, i.e., environment, economy, and society.

   There are about 40 attributes/indicators (lowest-level criteria), and about 20 higher-level criteria. Moreover, the criteria are of two (mathematical) types: quantitative and qualitative.

2. Four sets of discrete alternatives corresponding to energy technologies (each set composed of about 20 alternatives) are given. Each set corresponds to the technologies and their characteristics developed for the corresponding country.[5] Each alternative is composed of an identifier and indicators' values (either numerical or qualitative).

3. The preferences of diversified stakeholders are elicited through the Web-based multicriteria analysis. Each stakeholder has a private data space for her/his preferences and the corresponding analysis. The preferences are expressed in terms of relative importance of the criteria.

4. Analysis of individual preferences and the corresponding solutions has been done by experts in the energy domain, policy-makers and advisors, members of non-governmental organizations, and researchers working in different areas.

5. The outcome of a multicriteria analysis of alternatives performed according to the preferences of each stakeholder has been used by the experts for the second stage of analysis.

6. At least two types of outcome from the multicriteria analyses done by the stakeholders were desired as the input to the second stage analysis:
   - Information about individual preferences for technologies analyzed independently; if possible this information should include a ranking (full or partial, ordinal or cardinal).
   - Clusters of technologies, each matching a cluster (corresponding to a selected similarity measure) of the preferences of stakeholders.

From an analytical perspective the class of problems is characterized by:

1. A medium-size set of alternatives, which was however clearly too large to consider methods using pair-wise comparisons by the users.

2. A large set of criteria organized in a hierarchical structure.

[4]Than the leaf/lowest level.

[5]The study was done for France, Germany, Italy, and Switzerland.

3. Criteria having diverse characteristics, including:
   - multimodal distributions of values,[6]
   - different types of criteria, i.e., numerical and ordinal.

4. A large number of diversified stakeholders with substantially different preferences; most stakeholders have rather limited skills in using formal analytical methods.

5. The need for analysis reflecting diverse preferences in a fair way.

The remaining part of this Section is organized as follows: We begin with a summary of the context of analysis (Section 2.1) and follow with an outline of the elements of the analysis in Section 2.2. The sets of criteria and alternatives are discussed in Sections 2.3 and 2.4, respectively. The problem specification is completed by the discussion of issues pertinent to the stakeholders in Section 2.5.

2.1 Context

2.1.1 The NEEDS Project, relevance to energy/electricity sectors and importance

The NEEDS project was intended to address the sustainability of electricity generation technologies and systems in a comprehensive, multi-criteria way, thus it focused on the use of multicriteria analysis as an essential methodology to assist individual decision-makers and groups in balancing the competing characteristics of different options in order to reach an option ranking in accordance with their preferences.

The electric industry is an important part of the overall energy sector for many reasons. Electricity serves as an energy carrier that transfers primary energy from many diverse sources to provide customers with a very wide range of end-user services. It is a uniquely flexible and high quality form of energy that is irreplaceable in many applications. Because of this, it has an important and increasing share of the end-use energy market. The sheer scale of its use means that the electric supply industry has a very large infrastructure with a wide range of significant impacts in all three areas that traditionally comprise sustainability, i.e. the economy, the environment and society. Such impacts include internal and external costs to customers and society, environmental burdens like airborne emissions, toxic and nuclear waste and resource depletion, and an array of health, risk and safety considerations. The size and life of the infrastructure also means that the sector has a large inertia, so changes like the penetration of new primary energy sources can take a long time to make a significant impact. As one example, electricity generation is a primary contributor to CO_2 emissions, but it is susceptible to reductions by switching to low or zero carbon primary energy resources or carbon capture, more possible due to the relatively low number of large, fixed (non-mobile) sources.

The NEEDS project intended to address the demand for improving sustainability in the electricity sector by assessing a wide range of economic, environmental and societal indicators for a range of generating technologies, and to extend this technology-specific

[6] Roughly speaking, multimodal distributions are characterized by values split into several disjointed subsets separated by empty subsets covering large ranges of values. Consider e.g., two subsets of values: the first composed of positive values smaller than 100, and the second composed of values larger than 100000. Typical statistical characteristics of such data is usually not adequate. For example, the average value is often far away from the closest value of a member of the set.

analysis to a limited number of scenarios for operating and expanding the electric sector in the future.

2.1.2 The MCDA problem as it applies to NEEDS

We use in this document the widely used term MCDA (Multicriteria Decision Analysis) because it covers a well developed field of Operational Research that provides methods and tools pertinent to our problem. However, we need to stress that our problem (described in detail below) substantially differs from typical MCDA problems (in which a decision-maker analyzes a decision problem together with his/her preferences). We deal with stakeholders and not with decision-makers, and these two groups are fundamentally different and so are their goals. Thus the aim of the analysis of the problem under consideration is to find relationships between the preferences of diversified groups of stakeholders and corresponding solutions (technologies or scenarios). This analysis has some similarities with decision-making therefore we also briefly discuss here multicriteria analysis of decision-making.

Decision-making is difficult in the electric sector for many reasons. The scale of the problem is very large, the range of impacts is very broad, and the time-scales involved can range from seconds (or less) for operation to decades (or more) for planning. In particular, the scale of the planning problem means that it is a very important one for many people, and the broad range of impacts means that there are inherent trade-offs between competing characteristics (e.g., cost versus emissions) - which in turn means that stakeholders are unlikely to agree. Different input assumptions, uncertainties and attitudes towards risk all further contribute to this disagreement. In particular, different groups such as utilities, regulators, customers and environmentalists all have different interests at stake (hence the term 'stakeholder') and their different points of view lead them to have significantly different opinions on how different planning options should be ranked, or what may be the *best* strategy for system operation or expansion. To further complicate matters, no single decision-maker exists. Instead, there are decision-makers within each stakeholder group, and these groups interact within a public policy arena where negotiation and political processes are the rule.

The NEEDS project contributed to support this complex decision-making process primarily by supplying it with a common basis of trustworthy information. The MCDA task in NEEDS particularly helped the decision-makers analyze technological alternatives and strategies, consistent with their preferences expressed in terms of the diversified set of criteria, in a clearly understandable and trustworthy way.

2.1.3 Why MCDA is needed

MCDA assists decision-makers in several different ways, according to the main problems experienced in making decisions on complex systems. In particular, the goal is to help make the decision-making process structured, explicit, clear and correct, so that not only is the ranking of alternatives right for each decision-maker's preferences, but the entire process serves as a clear basis for debate with others. Some of the typical problems are very briefly mentioned below:

Attainable goals: In order to make a good decision, it is necessary to specify preferences that lead to attainable goals (i.e., feasible values of criteria). This means it is necessary to clearly establish priorities and trade-offs between competing goals. MCDA assists in this by using clear procedures to establish preferences, and identifying a solution that best corresponds to the specified preferences.

Cognitive limits: Most people can intuitively select an alternative from a small set by considering a small number of criteria. But for a large number of alternatives and/or criteria intuition and/or experience need to be supported. This problem is exacerbated by mixing quantitative and qualitative indicators and preferences that are often discontinuous, non-linear, and have threshold values. MCDA provides an analytic structure that can clearly indicate why a given set of preferences (expressed in terms of criteria) results in a certain efficient solution; in some cases a certain ranking of alternatives can also be provided.

Preconceptions: It is typical for a decision-maker's initial preferences (expressed in terms of criteria) to result in a selection of alternatives that is inconsistent with the stakeholder's own preconceived characteristics of a solution. The stakeholder is confronted with the choice of modifying his/her expectations about the solution, or her/his preferences (or both) until a consistent result is achieved. Only multicriteria analysis can really demonstrate such inconsistencies, and assist in resolving them iteratively.

Group differences: It is rational for a heterogeneous stakeholder group to disagree, and often necessary for them to reach some joint decision. MCDA can clarify the reasons for disagreements and form a basis for discussions and negotiations. Some MCDA methods are also more formally combined with joint-resolution methods (although not in this project).

2.2 Elements of multicriteria analysis

Multicriteria analysis is composed of several interlinked elements, which do not form a linear process, i.e., some of them are developed in parallel, and/or can be modified during the analysis. We list these elements in the order in which they are discussed below:

1. Definition of criteria.
2. Definition of alternatives.
3. Preparation of the problem analysis.
4. Problem analysis composed of a sequence of two steps:
   - specification of user/stakeholder preferences, and
   - finding a solution (an alternative, or a ranking of alternatives) best corresponding to the preferences.
5. Analysis of results.

The essence of multicriteria analysis is actually the sequence of modified preferences based on the analysis of solutions corresponding to previously specified preferences. The reason for such a sequence is the commonly known fact that typically, (especially in an initial stage of problem analysis) solutions corresponding best to preferences differ substantially from the expectations of the user. Therefore the user typically needs to modify his/her preferences in order to find solutions that are close enough to the goals (values of criteria) that are both attainable, and have trade-offs between criteria that fit the user preferences.

2.3 Set of criteria

Criteria are used for measuring the performance of alternatives. Therefore the choice of a set of criteria is of primary importance for the analysis of alternatives. The set of criteria used in the MCA-Needs resulted from a comprehensive study made by the RS2b team that is documented in [1, 9, 19, 20, 22]. Moreover, the survey on criteria [2] provided feedback from the stakeholders. Therefore here we only summarize the main considerations taken into account by this study.

The main considerations that were taken into account for the choice of specific indicators included:

- Results of a literature survey on sustainability indicators in general (past experience).
- Social indicators were developed within a dedicated activity, which was a pioneering effort that also included a Delphi exercise.
- Catching the essential characteristics of technologies and enabling differentiation between them.
- Assuring that indicators are representative (but not necessarily complete).
- Keeping the number of indicators at a reasonable level and striving for a certain balance in terms of the number of indicators.
- Trying to avoid excessive overlapping.
- Aiming at limited aggregation of indicators provided that this involves no or minimum subjectivity.
- Assuring practicability and feasibility; in particular having confidence that the values of indicators would be available on-time to be used in the analysis.

Important features of the proposed set included:

- The selected indicators are distributed between the three sustainability dimensions, i.e., environmental, social and economic.
- The overall structure and selection made resulted from the stakeholder survey.

There are different types of indicators (e.g., quantitative and qualitative), some of them having a multimodal distribution of values. Based on past work on similar projects considering sustainability indicators, the final set of indicators (for each country) is around 40. Such indicators are often divided into the *three pillars of sustainability*, i.e., those relating to the general areas of the economy, environment and society.

The hierarchical structure of the criteria and indicators is illustrated in Fig. 2. The indicators are included into hierarchical criteria structure having up to four levels within each of these three pillars. This structure is somewhat relevant to the ranking analysis, but more important to preference elicitation, where the addition of such a structure can give decision-makers a framework for specifying their preferences. Thus the indicators are considered as the lowest-level criteria, and about 20 higher level criteria have been defined. The higher-level criteria have no physical values, they only serve for specifying multiplicative preference in the criteria tree. Note that preferences cannot be specified effectively[7] for criteria that have only one child criterion; the circles attached to the criteria names in Fig. 2 indicate that preferences were specified for the corresponding criterion.

Therefore altogether about 60 criteria were defined. For issues of sustainability, 60 might also be considered a reasonable upper bound on the number of criteria, because

[7] Because the normalized importance weight for such a criterion is equal to 1, irrespectively of the relative criterion importance that would be specified by the user; see [7] for the definition of weights in the criteria hierarchy.

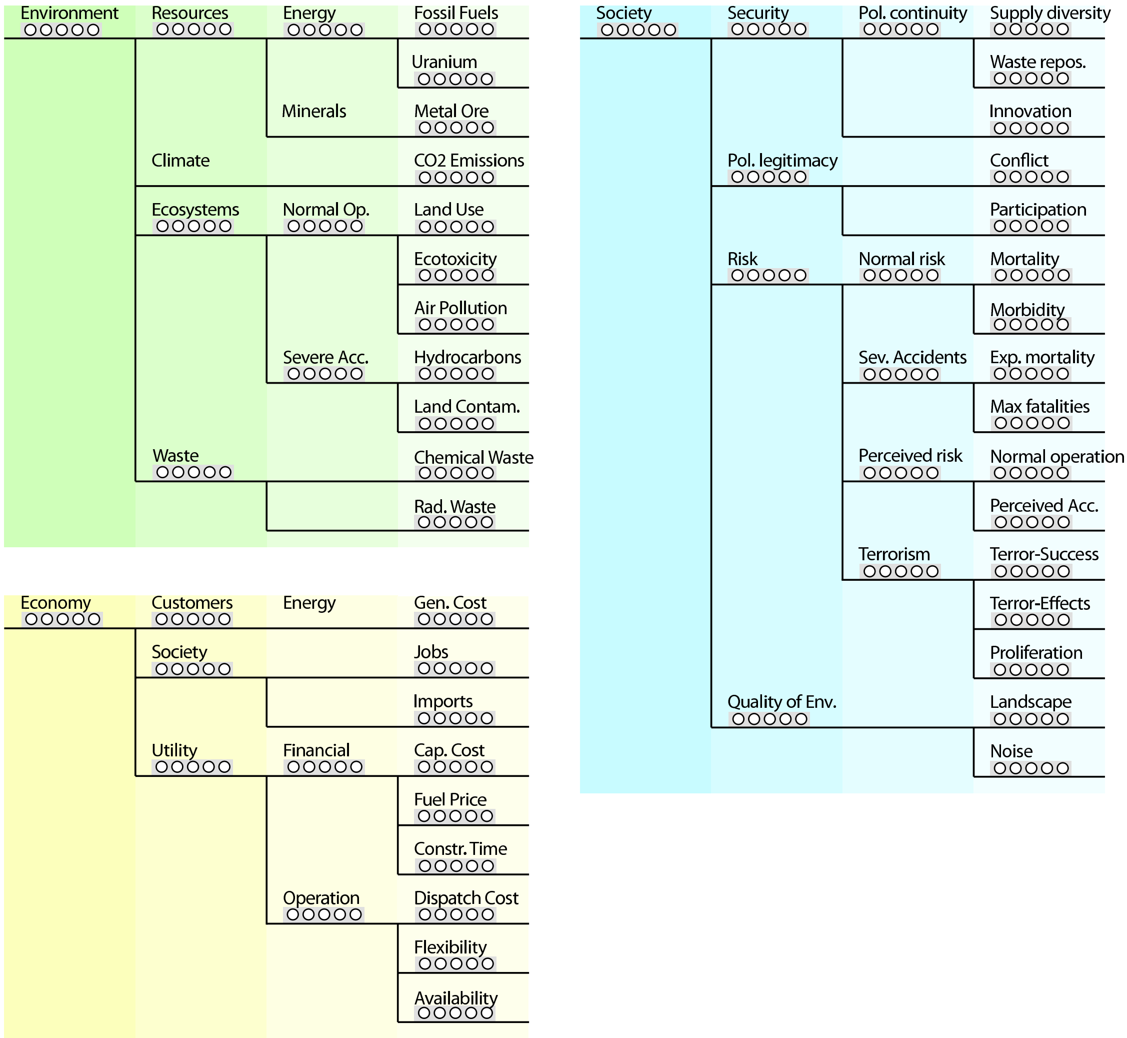

Figure 2: Hierarchy of criteria and indicators.

adding further criteria dilutes the impact of those already present. For quantitative attributes, the value represents an actual value of the indicator. For qualitative indicators, the value corresponds to an *order*, i.e., a (real or integer) number inducing an order within the set of admissible values of the corresponding indicator (e.g., very bad, bad, average, good, very good). It is assumed that for maximized criteria the higher number corresponds to a higher preference. Partial order is allowed (i.e., duplicate values of the *order* attribute).

2.4 Sets of alternatives

A set of alternatives was developed for each of the four countries. The alternatives define corresponding sets of electric generation technologies. The set of alternatives is broad enough to be interesting to all stakeholders, and specific enough that results are calculable. The definition of alternatives includes both common and technology-specific assumptions (e.g., fuel prices and fuel efficiencies), system boundaries, etc. The number of generation technologies is about[8] 20 for each country. This covers a range of technologies for the different fossil fuels, nuclear plants, and a selection of renewable generation options.

2.4.1 Preparation of alternatives

Each alternative/object is described by values of criteria (often called indicators). Each criterion is either numerical (quantitative or cardinal) or non-numerical (qualitative or ordinal). The following table illustrates the data content for a set of m alternatives in the form of a matrix, each identified by an identifier (here defined as $alternative_i$) and characterized by values of n criteria; in other words, the value of j-th criterion for i-th alternative is defined by $v_{i,j}$.

criteria alternative id	$criterion_1$	$criterion_2$	...	$criterion_n$
$alternative_1$	$v_{1,1}$	$v_{1,2}$	...	$v_{1,n}$
$alternative_2$	$v_{2,1}$	$v_{2,2}$	...	$v_{2,n}$
...	...	...	...	...
$alternative_m$	$v_{m,1}$	$v_{m,2}$	...	$v_{m,n}$

Table 1: Illustration of specification of alternatives.

The values were defined in the units specified for each indicator. No scaling was applied to the indicators' values of alternatives during the data preparation and verification. The assigned values were transformed into achievement measures during the problem analysis.

2.5 Stakeholders

2.5.1 Context

Planning and decision making in the electric power sector should consider stakeholder preferences. Thus to achieve a reasonable quality of analysis (that could be a major factor in a decision-making process) it is critically important to adequately represent the stakeholder preferences. However, this is not only important but also a very difficult issue because of two sets of problems.

Firstly:

- Preferences are substantially different for different groups of stakeholders.
- Stakeholders typically do not have experience in the processes of formal analysis.
- Stakeholders have diverse backgrounds, thus not many of them were able/willing to specify preferences for all criteria (that are specified on the lowest level in a rather detailed way).
- The rather short time period (between the set of alternatives being available and when the results of analysis are due).

Secondly, it is known (from the properties of the mathematical programming problem corresponding to any method of analysis of our problem) that:

[8] Difference between countries reflect the actual resource availability and operating conditions.

- The relation between changes of preferences and the corresponding changes of solutions is nonlinear and discontinuous, i.e., in many situations even large changes of preferences do not result in (substantial) changes of solutions, while in other situations a very small change of preferences results in a qualitative change of a solution.
- Even for problems that are easier from the mathematical programming viewpoint (e.g., continuous linear models), preferences specified by a stakeholder may result in solutions inconsistent with his/her preconceived characteristics of the corresponding solution; such inconsistencies should be resolved and this is only possible by either changing the preferences or expectations about a satisfactory solution. This is a typical situation, and the main argument for interactive problem analysis.

It is commonly agreed that elicitation of stakeholders preferences must include computerized interaction with each stakeholder during which she/he is supported in the analysis of the correspondence between her/his desired goals and the corresponding attainable outcomes/results. However, it is also commonly agreed that designing and implementing an effective interaction is a challenging task. The challenge is due to the fact that elicitation of preferences is based on learning about the problem through its analysis, and in the case of many users/stakeholders this had to be unsupervised learning. Thus the interaction has to be carefully designed to address the needs and expectations of stakeholders with a wide spectrum of backgrounds and goals.

2.5.2 Information that was provided to the stakeholders

Each stakeholder was provided with two sets of information pertinent to specification of preferences:

- General information common to all stakeholders, about the problem, elicitation of preferences, etc.) and characteristics of the sets of alternatives. The latter should contain:
  - ⋆ a definition of each indicator,
  - ⋆ basic information regarding the value distribution of each indicator,
  - ⋆ basic information regarding the distribution of numbers of alternatives along values of each indicator,
  - ⋆ the pay-off table (best and worst values of each indicator),
  - ⋆ information about clusters of solutions corresponding to "selfish optimization" of each indicator,[9]
  - ⋆ specification of the criteria and their hierarchical structure.

  This information should be provided as part of a Web-site to be developed for on-line elicitation of preferences.
- Individual information corresponding to various preferences specified by the stakeholder. This information should enable a stakeholder to modify her/his preferences until a satisfactory solution is found, and should include:
  - ⋆ providing a solution corresponding to a specification of preferences,
  - ⋆ various ad-hoc information, e.g., number of feasible alternatives for lower bounds specified on values of a set of criteria,
  - ⋆ optional characteristics of classification/rankings of solutions corresponding to a set of preferences.

[9] The best value of each indicator has an associated set of alternatives. Some of these sets are likely to overlap, and this might be interesting information.

2.5.3 Use of the preference information in a problem analysis

In order to justify the proposed requirements for the elicitation of stakeholder preferences we need to summarize how preference information is used.

The preference information is used to compute parameters of a scalarizing function. There is a class of formalized methods for model[10] analysis that uses preference information for the calculation of parameters of a scalarizing function, i.e., a function that associates a number with each solution (an alternative in our case) that measures the quality (goodness) of the solution. For a multicriteria analysis such a function maps a multidimensional space of criteria into a one-dimensional real-number space that induces (at least partial) order in the solution space. Therefore, various multicriteria methods differ by:

- specification of scalarizing function,
- mapping of the preferences into parameters of the selected scalarizing function.

Thus, the properties of various methods of multicriteria analysis can be considered by examination of the properties of:

- the corresponding scalarizing function,
- the properties of sets of criteria values.

The latter is especially important for the analysis of discrete alternatives with multimodal distribution of criteria values.

Typical users do not consider the mathematical properties of their problems. They reason in terms of trade-offs between criteria. Such trade-offs alter with changes of criteria values (e.g., a ”weight” for costs is much higher for ”expensive” alternatives than for ”cheap” ones). Therefore specification of trade-offs is often done for a given solution rather than for the whole range of criteria values (e.g., how much more am I willing to pay for an alternative which has a lower emission of pollution). Moreover, users analyze the quality of a solution in terms of the acceptability of the values of criteria (e.g., is the cost within my budget?, is the emission level acceptable?). Hence, users focus on a subset of criteria whose values the user considers unsatisfactory, and try to improve them by changing preferences. Of course, by improving the value of even one criterion, the value of at least one other criterion must worsen, and this may be not acceptable, which in turn calls for another modification of preferences.

This short summary of the essence of multicriteria analysis shows that an interactive procedure is practically required for a proper specification of preferences.

2.5.4 Preference information from stakeholders

Generally, the information provided by a stakeholder needs to be sufficient to represent his/her preferences in terms of criteria (e.g., as trade-offs between criteria values). These trade-offs are typically different for various ranges of criteria values at the lowest hierarchy level (i.e., corresponding to the attributes). Consider, for example, trade-offs between changing values of two minimized criteria, cost and emission level. Such trade-offs are typically different for:

- expensive, medium-cost, and cheap solutions, and/or
- large, medium, low emission levels.

[10] A set of alternatives can also be considered/represented as a model.

For expensive solutions (and the corresponding low emission levels) a substantially stronger preference is attached to the cost reduction than for cheap solutions. In other words, the relative importance of costs (compared to the emission level) is typically much higher for expensive than for cheap solutions. Similarly, the relative importance of the emission level criterion decreases when one moves from high to low emission levels.

There are several ways of dealing with trade-off specification. For our problem (characterized by large numbers of criteria and alternatives) approaches based on pairwise comparisons are not practicable. This reduces the choice of methods for trade-off specification to:

- Direct specification of weights (for criteria and for scalarizing functions).
- Indirect specification of weights, e.g., by specification of relative importance of criteria.
- Indirect specification of parameters of scalarizing functions by selection of:
  - ⋆ aspiration (the desired criterion value) and reservation (the worst criterion value the stakeholder is willing to accept) values for each criterion, or
  - ⋆ aspiration or reservation values for each criterion, and information about trade-offs between criteria at the selected aspiration (or reservation) point.

Additionally, the following preference information from stakeholders could be useful for a better support of the preference elicitation process:

- Specification of an acceptability (threshold/veto) level for criteria (equivalent for rejecting alternatives having worse values of the corresponding criteria).[11]
- Optional specification of sets of compensatory criteria. Criteria are compensatory when an increase of the value of one of them by a given value from a relative scale can be rationally substantiated to compensate a deterioration of another criterion.
- Optional specification of trade-offs between a selected subset of criteria (e.g., answering questions like *"if you want to improve the value of this criterion then select criterion/criteria you agree to worsen."*)
- Optional, based on intuition, selection of best and worst alternatives. This information was not used for the representation of stakeholder preferences; it can be used in the final analysis of the problem, including various characteristics of stakeholders.

Elicitation of stakeholder preferences was done through the Web-base interactive multicriteria analysis tool called MCA-Needs described in Section 5. Moreover, for the second stage of analysis (done by analysts) some information about profile of each stakeholder was required. Organization of this process is also discussed in Section 5.

3 Problem analysis

3.1 The purpose

The purpose of the NEEDS project was to support the EU decision-makers who can influence expansion planning for the electric generation sector. The decision-makers need to make good quality decisions, consistent with their preferences, also taking into account the preferences of stakeholders. NEEDS was intended to support decisions that enhance sustainability in the electric sector, and ensure that a quality information base exists to support these decisions.

---

[11] This approach appears to be a much better way of eliminating some alternatives, than to attempt to do so by playing with weights/reservations.

The report [21] summarizing multicriteria analysis was a major factor in such a decision-making process. The purpose of the multicriteria analysis using MCA-Needs was to provide a basis for analysis of future energy technologies, and to report on stakeholder preferences on criteria characterizing them; these preferences were expected to substantially differ amongst groups of stakeholders. Thus the analysis attempted to fairly account for these differences and resulted in clusters of solutions corresponding to clusters of preferences. It was however beyond the scope of the NEEDS project work to attempt any type of analysis needed for supporting a group decision-making process, consensus building, or negotiations. However, the authors stress that such an analysis would substantially enhance the quality of the decision-making process. Thus, the main target of the MCA-Needs remained to enable a multi-criteria based analysis of a set of generation technology alternatives.

The analysis done by the RS2b team was composed of two stages, each of them summarized in the following subsections.

3.2 Individual stakeholder analysis

This analysis was done by each stakeholder individually through the Web-based application supporting interactive multicriteria analysis of alternatives (using data provided by a data server, see Section 4.2). The functionality of this application is documented in detail in [12].

The basic result of each individual analysis was a Pareto efficient solution (a technology) that corresponded best to the stakeholder preferences (expressed in terms of relative importance of criteria), and the corresponding trade-offs between values of the underlying attributes. Additionally, information about the corresponding ranking of alternatives was provided although it was known that due to the nature of the problem a ranking may not be stable, i.e., even small changes of preferences can result in rather different rankings.

3.3 Analysis of results corresponding to stakeholders' preferences

This analysis was done by the PSI energy experts in consultation with IIASA modeling experts, and is documented in [21]. The results of this analysis were used in the report submitted to the decision-makers and made available to the stakeholders.

The following types of analysis were explored:

- Clustering of preferences (and possible correlations with categories of stakeholders) for various similarity measures given by the analysts.
- Analysis of possible correlations between clusters of preferences and clusters of the corresponding results.
- Analysis of distributions of solutions (technologies/scenarios).
- An attempt to find (possibly partial) rankings, if stable rankings are possible for the given sets of alternatives and stakeholder preferences.
- Clusters of solutions (technologies/scenarios) corresponding to clusters of preferences (the latter possibly correlated with clusters of stakeholders' categories).
- A partial ranking of solutions (technologies/scenarios) within clusters of solutions.
- Identification of a subset of ”stable” solutions (those which are typically either ”very-good” or ”bad” or ”in the middle”), and ”jumping” solutions (which for small changes of preferences are either good or bad).

Given the characteristics of the problem, the following types of analysis were not possible:

- Aggregation of stakeholders preferences, and using them as ”representative” preferences for multicriteria analysis of alternatives.
- Reliable rankings of solutions.

4 Requirements for MCA-Needs

The requirements are summarized here from two perspectives: functionality from the user point of view, and requirements for the infrastructure and organization.

4.1 The user perspective

An appropriate elicitation of stakeholder preferences is typically difficult but – as discussed in Section 2.5 – it is especially challenging for the problem described in this report. Therefore we provide here a much more detailed (than for other elements of the analysis described in this Section) justification and description of the process.

Communication with stakeholders is extremely difficult because there is a gap between the information that is required by the analysis method and the language in which the problem is communicated and understood by stakeholders. Therefore, the communication method is a key element in gathering proper information from the stakeholder, using it in the decision process and communicating the results of the decision. Moreover, a process of preference specification is not stationary, i.e., even very experienced users of multicriteria analysis tools change their own preferences in a rather discontinuous/erratic way. Therefore it is important to repeat here the arguments presented in Section 2.5 that justify the need for an interactive (repetitive) process of elicitation of preferences. This is a necessary condition to acquire a reasonably good representation of stakeholder preferences.

Given the large number of stakeholders (over 3,000 were invited), it was decided that the elicitation of stakeholder preferences would be done via a Web-based interactive multicriteria analysis, which could provide diversified characteristics of a solution corresponding to a current specification of preferences, and helped (by providing pertinent information) to modify those preferences in a way that the next solution would better fit the expectations/preferences of the stakeholder.

Both the number of stakeholders invited to make the MCA, and the tight time-table of the whole NEEDS project (which left a rather short period of time between the alternative description data being available and the results of the MCA being due) made a Web-based survey directly linked with a data server to be the only solution acceptable from the project management point of view. After a careful analysis, the following three key assumptions were made for the MCA that served as the survey of the stakeholders’ preferences:

- **Survey size** - over 3,000 of stakeholders were invited to use the MCA-Needs for multi-criteria analysis of the assigned problems (technologies in a selected country from the four countries: France, Germany, Italy, and Switzerland).
- **Survey form** - Due to the large number of stakeholders invited to the survey it was clear that it was impossible to perform individual preference elicitations, either in

person or by phone. Therefore it was decided to develop MCA-Needs, the Web-based interactive multi-criteria analysis tool.

- **Scope of survey** - the survey length due to the response rates has two effects on the choice of multicriteria analysis method. It would be desirable to use more than one multicriteria method on the alternative and preference data, in order to compare how well the different rankings corroborate each other. However, this would require elicitation of preferences needed by each analysis method. Therefore it was decided to examine several methods but to provide all the stakeholders with only one method selected by the PSI team.

It was agreed that the following features of the multicriteria analysis method, and its implementation were desirable:

Ease of use: The MCA-Needs was used by both stakeholders (who are typically not experienced in analytical tools) and experienced analysts. Therefore specification of preferences had to be done in terms that were understood without knowledge of operational research. Also explanations of all pertinent terms (used for specification of preferences, and for the definition of criteria and alternatives) had to be easily accessible through hyperlinks in the Web-based MCA. Moreover, preferences needed to be specified through a user-friendly interface. Finally, for the Web-based MCA, at least a Pareto-efficient solution corresponding to the specified preferences had to be easily available; preferably, assistance in assessing trade-offs between criteria should also be provided.

Transparency: Transparency focuses on the two elements of clarity (easy to understand), and trustworthiness. These both follow along the analytic chain, so it should be easy to see and trust:
- the input assumptions for the analysis of alternatives,
- the analytic process (e.g. the modeling methodology),
- the multicriteria analysis method.

Treatment of preferences: A stakeholder should be confident that the analysis method conforms to the form of his preferences, not the other way around. Preferences for thresholds, vetoes, non-linear scalarizing functions, etc. should be addressed.[12]

Ease and speed of iteration: Using the method and the corresponding tool should be a learning process, and the first specification of preferences should be the start of an exploration process. The iteration process had to be quick and interactive in order to satisfy the stakeholders and motivate them to spend more time in refining and verifying their preferences.

The following, more specific features, were also considered:[13]

1. Is the considered method and the corresponding tool available and can be adapted with a limited amount of resources, or does the method need to be developed and the tool to be implemented ?

[12]Note, that this requirement contradicts the requirement for the *Ease of use*, because informed specification of such parameters requires analytical skills.

[13]It is clear that there is no method which conforms to all of these criteria.

2. Availability (free or license, restrictions, price).
3. Has method/tool been successfully used for energy applications relevant for NEEDS?
4. Simplicity, transparency, easy to use, interactivity.
5. Mathematical correctness.
6. Internal consistency checks.
7. Suitable for large amount of applications.
8. Processing, analysis and presentation of results.
9. Sensitivity analysis capability.
10. Compatibility with the intended elicitation of preferences.
11. Possibility to use *"simulated"* typical preference profiles.
12. Expandability in the future.
13. Can minority views be considered?
14. Non-discriminatory treatment of technologies.

Moreover, it was necessary to decide on whether to provide the stakeholders with one or more multicriteria analysis methods. There are advantages and disadvantages in both cases. Stakeholders with analytical skills would most likely prefer to make analysis using several methods while others would likely be confused when confronted with several methods even if they shared the same way of specifying preferences.

4.2 Infrastructure and organization

The many participants of the analysis process (stakeholders), the serious time constraints (short time between availability of data and required output), and the many diversified data flows involving various teams implied the necessity for an efficient computing infrastructure.

Depending on the final selected method, the required computing resources might have been substantial (especially, if many stakeholders would perform interactive analysis simultaneously); therefore it was desired to have a possibility for the easy use of a computational grid when a peak of computations occurs. Such a computational grid was prepared, based on SGE (Sun Grid Engine), and a network of unix workstations.

Before the MCA-Needs was ready for extensive testing it was not clear how many computing resources were actually needed for the on-line evaluation of preferences. However, it was clear that data handling posed a serious challenge unless an effective data server was provided. The most rational solution appeared to be a Web-based data server handling all data necessary for the analysis, including:

- Definition of criteria and alternatives, including all necessary dictionaries, see Section 2.3.
- Data needed for Web-based MCA,
- Representations of stakeholder preferences (updated through the Web either by directly linking the survey forms with the DB, or by a dedicated interface to be used by staff processing paper surveys); versioning and automated documentation needed.
- Providing data for MC tools through either a direct link to the DB or upload/export of data from/to CSV files.

Such a data-server was implemented using modern technology for the development of Web-based and distributed applications, and was based on a transactional professional database.

5 Implementation

It should be stressed that the reported activities have been a pioneering work in the field of integrating public participation with science-based support for policy-making. While there is a lot of experience in various forms of public participation in policy-making, there was no attempt to involve a large group of stakeholders in interactive multicriteria analysis. Moreover, the analyzed problem was complex by itself, i.e., there has been no suitable method for its analysis. Therefore the team that implemented the analysis had to cope with several interlinked challenges, including:

- development of new methods for multicriteria analysis of the underlying class of problems; the methods had to use a simple way of specification of preferences that were also suitable for users having no experience in mathematical programming,
- designing and implementing an interface to these methods suitable both for researchers and for stakeholders with almost no analytical skills typically used in model-based problem analysis,
- design and implementation of a Web-site for multicriteria analysis by a large number of inexperienced stakeholders using advanced methods of multicriteria analysis.

This Section summarizes the main elements of the implementation, and discusses in more detail those elements which are likely to be of interest of both research communities and practitioners involved in science-based support of policy making.

The requirements for multicriteria analysis specified during the first stage of the project, and summarized in Section 4 had to be met within the available time and resources, including availability of data for specification of the underlying problem, as well as with the state-of-the-art in both methodology of the multicriteria analysis and software tools supporting such analysis. This in turn has determined sets of feasible decisions regarding the actual implementation of the analysis.

5.1 Overview of the problem analysis

The structure of the analysis of future energy technologies (here called alternatives) can be considered as a process composed of three stages:

1. Preparation of alternatives, including:
   - Selection of the set of attributes characterizing each alternative, and evaluation of the values of the attributes.
   - Selection of the hierarchical criteria structure to be used for the multicriteria analysis (where the lowest level criteria were the attributes, and the three highest level criteria were the three pillars of sustainability).

   Four sets of alternatives and criteria were prepared for four countries, namely France, Germany, Italy, and Switzerland. Preparation of the alternatives was done by a concerted set of activities documented in detail elsewhere, therefore we don't comment on this part of the process here.

2. Individual multicriteria analysis of alternatives, the part of the process which is the main focus of this report.

3. Analysis of the results obtained from the multicriteria algorithms applied to preferences of individual stakeholders. This analysis was done by the analysts to provide

a basis for the final report that was submitted to decision-makers and to stakeholders. Clustering algorithms were applied to identification of groups of stakeholders with similar preferences, and for clusters of the corresponding solutions. Finally, an analysis of the characteristics of clusters of solutions has been made to detect if rankings can be established for at least subsets of solutions (technologies or scenarios).

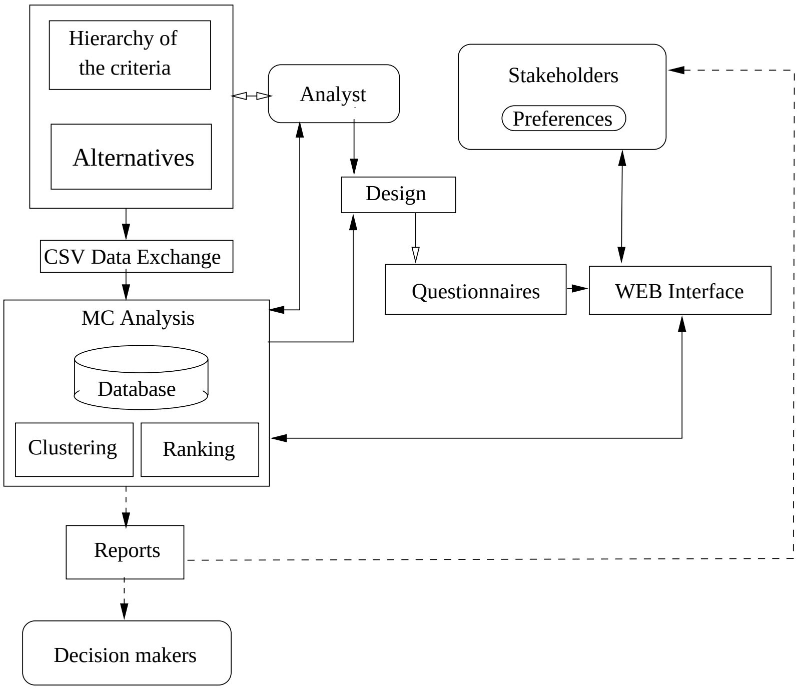

Figure 3: Main components of the analysis process of the future energy technologies.

Here we focus on the multicriteria analysis of alternatives performed by the stakeholders. The structure of this analysis is illustrated in Figure 3. The presentation of the implementation of this analysis is composed of the following two parts discussed in the corresponding sections:

- basic assumptions, and
- architecture of the MC implementation.

5.2 Basic assumptions

5.2.1 General assumptions

The analysts actively participated in the process of problem definition (definition of alternatives and criteria) as well as in the process of defining the MCA-Needs functionality. The analyst team also provided comments and feedback for the design of the MCA-Needs, and in particular for the specification of the way in which the stakeholders specified their preferences.

Another requirement for the MCA-Needs was to design it in such a way that the stakeholders were able to observe in real time the influence of his/her preferences on the corresponding solutions, and then change his/her preferences until a satisfactory solution was found. Such a process supports learning about the problem during the specification of preferences. This approach has significant advantages over static questionnaires, and stakeholders should be more motivated to use the Web interface. It should be stressed that most of the multicriteria analysis methods assume interaction with the decision makers or stakeholders. Therefore, the use of static questionnaires to elicit the preferences of the stakeholders has limited value in comparison to an interactive tool accessible by the Web interface, which in turn provides real-time access to a multicriteria tool operating on the data provided by the data server.

Moreover, for a Web-based elicitation of preferences the results can be stored directly in the database, and thus allow the stakeholder to optionally continue the analysis later. The Web-interface also provides efficient ways of designing user-friendly surveys, including context sensitive help and tutorials.

The data for criteria and alternatives for each of the four analyzed countries were uploaded to the data-server. While doing this the analysts performed a consistency check of the data loaded to the data-server, and assured that the final sets of data were suitable for the analysis.

For the second stage of the analysis, it was necessary to collect information about the profiles of the stakeholders. This information was collected in a separate part of the survey (implemented by another team and on another hardware facility) in order to not keep personal preferences together (i.e., in one database) with personal profiles of the stakeholders.

5.2.2 Specification of the user preferences

The summary of various approaches to preference specification contained in Section 2.5.4 reflects the state-of-the-art of methodology for multicriteria analysis. However, the key factor for selecting a way of preference specification for the MCA-Needs was the requirement that such a specification had to be simple enough to effectively support also the stakeholders without analytical skills in expressing their preferences. One should also recall that the analysis involved about 60 criteria, which obviously eliminates many of the above outlined methods of preference specification.

After a number of discussions, the team responsible for the implementation of the MCA for the NEEDS projects has decided to use a very simple method, namely specification of relative importance of each criterion by selecting one of the following discrete importance levels, each having an intuitive characteristics, namely:

- vastly less important than average,
- much less important than average,
- less important than average,
- average importance,
- more important than average,
- much more important than average,
- vastly more important than average.

It was also possible to entirely ignore a criterion. This simple approach proved to be effective in the sense that it was not only easy to be understood and used, but also supported analysis of the whole Pareto-set (i.e., it was possible to select each efficient alternative), and it was relatively easy to find an alternative with a better value of a selected criterion. It is interesting to note that this way of specification of preferences effectively supports also analysis of other problems, see [7, 11] for more details.

Finally, we stress that over thirty new methods for multicriteria analysis of the underlying class of problems (characterized by a large number of alternatives, and of criteria) were developed, and extensively tested. After the testing, one of these methods was made available for the actual analysis by stakeholders. It is interesting to note that the comparative study of the methods (made after the survey using its results) has shown [7] that in most cases (i.e., for distinct preferences) several different methods provided the same Pareto-optimal alternative.

5.3 Architecture of the Web-based MCA

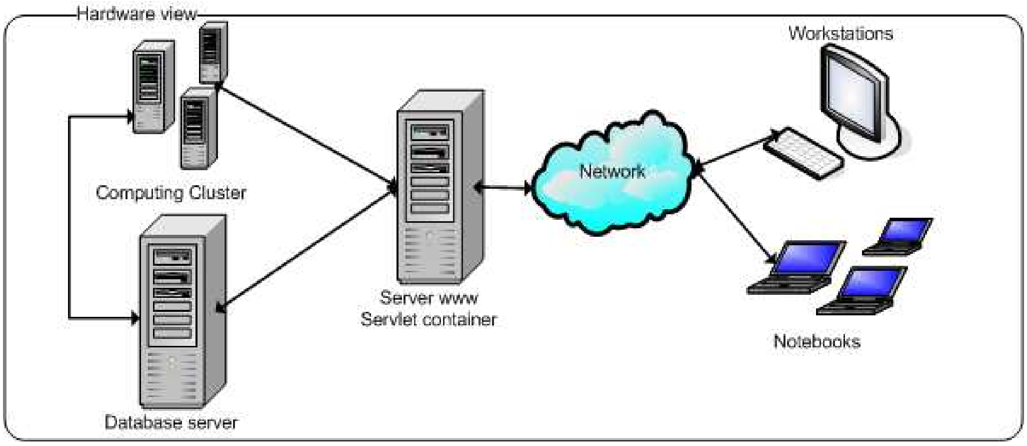

Figure 4: Architecture of MCA (hardware view).

MCA-Needs was developed by applying the internet and database technologies. The general architecture of the MCA is characterized from two perspectives, namely, hardware and software.

The hardware perspective is shown in Figures 4. The users can access the MCA from any computer connected to the Internet and running a web browser. Most popular browsers are supported, and no browser plug-ins are required. The only requirement is to allow the opening of pop-up windows generated by applications run on the www.ime.iiasa.ac.at domain. Therefore users that do not routinely allow pop-up windows needed to change their permissions to allow opening pop-up windows by the IME-IIASA site.

The MCA software runs on the IIASA Sun-Solaris servers. The software has modular structure, and the modules are designed to work in the distributed environment illustrated in Figure 4. In particular, there are:

- a www server,
- a servlet container,
- a database server, and
- a computing cluster.

In the near future there are plans to extend the MCA functionality to handle (possibly large) linear models. Optimization of such models requires substantial computing resources. Therefore, a computing cluster might be configured using e.g., SGE (the Sun Grid Engine).

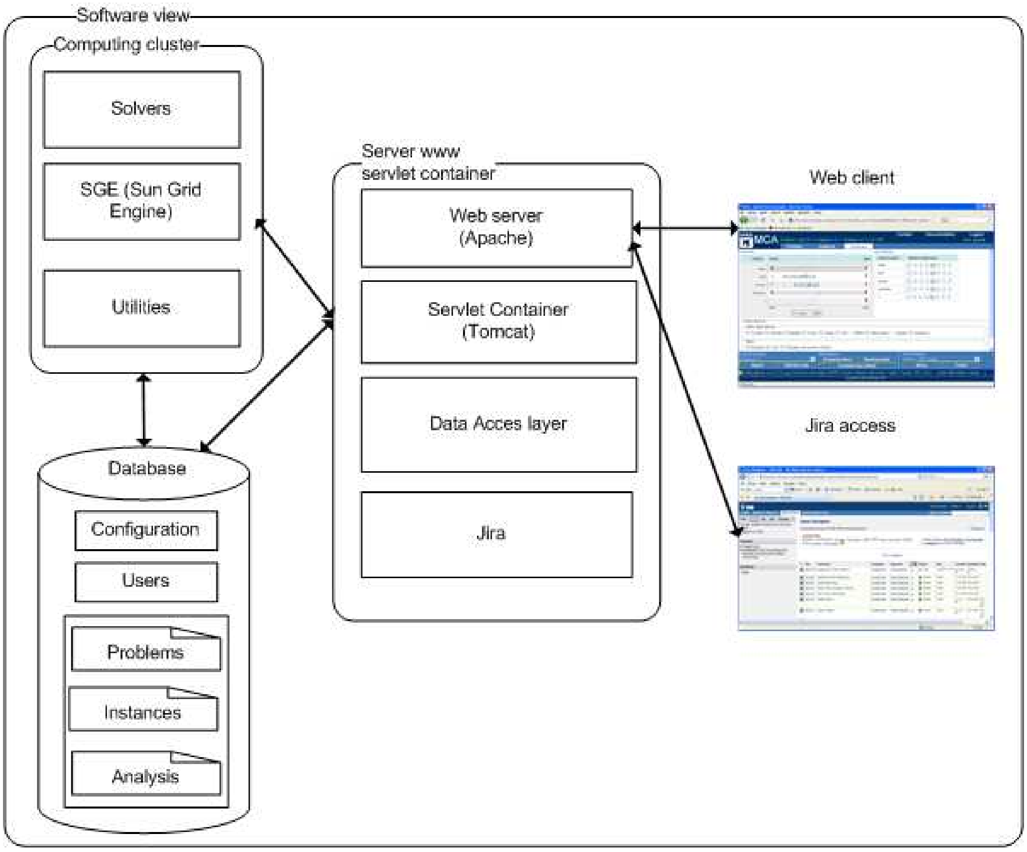

Figure 5: Architecture of MCA (software view).

The software perspective is illustrated in Figure 5. The following components were implemented[14]:

- web server (Apache),
- servlet container (Tomcat),
- database (Oracle),
- web clients for graphical user interface (Java, Java Server Pages),
- solvers for the multicriteria optimization (dedicated application in C++),
- Sun Grid Engine, and
- various utilities for maintaining contact with the users, reports for the organizers, etc. (implemented in C++, Java, JavaScript, Perl, csh, and API to Jira).

The software provides the desired functionality, including handling of data, specification of the user preferences, running the solvers of the underlying optimization tasks,[15] displaying the results of analysis to the users, providing reports for the analysis administrators, etc.

Most parts of the MCA software were developed using Java technology and JSP (Java Server Pages). The graphics are based on the jfreechart (www.jfree.org) library. The

[14] In parenthesis the currently used software is noted.

[15] Used for selecting Pareto-optimal alternatives corresponding to the specified preferences.

solvers have been implemented in C++. All MCA applications communicate through the Oracle data base, which stores all pertinent data, including:

- configuration of the software, in particular interface between the GUI and solvers,
- data about users, including their roles, privileges, contacts,
- specification of the problems to be analyzed,
- specification of instances of each problem,
- private data space for individual analyses.

Such a solution is not only very efficient from the point of view of the performance of the user interaction, but also at solving the underlying optimization problem; the modular structure of the MCA components is also effective for the process of software development and maintenance.

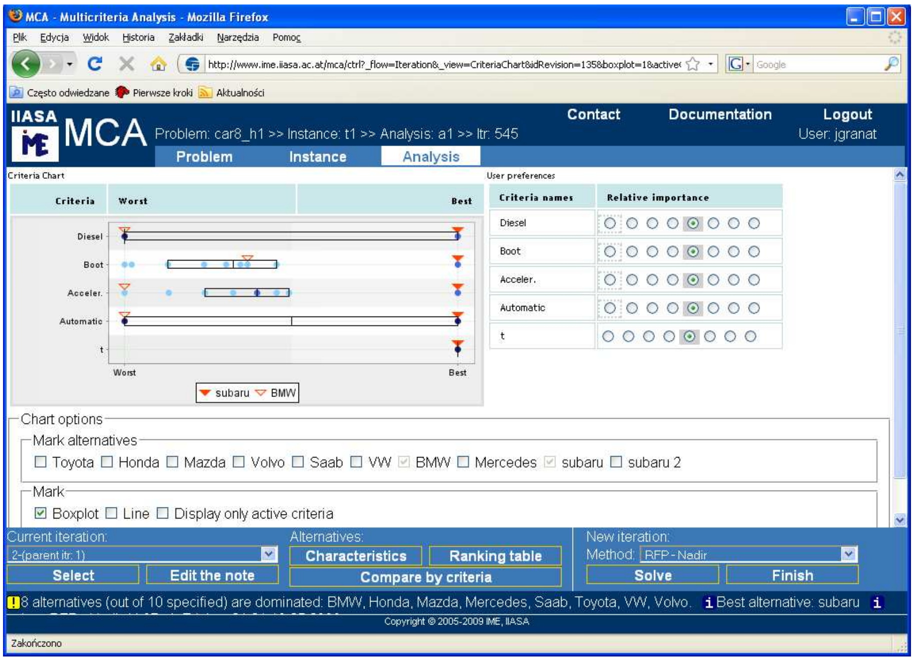

Figure 6: The main user-interface screen.

An example of the the main user-interface screen is shown in Figure 6. This screen contains all information needed for a basic analysis of the Pareto-optimal alternative corresponding to the specified preferences. The implemented way of preference specification is summarized in Section 5.2.2, and the selection is done by selecting a corresponding button from the panel located on the right side of the screen.[16] The trade-offs between the criteria values are shown in the parallel coordinate graph on the left side of the screen. The controls available to the user are organized into two panels: the bottom one provides controls for additional functions for analysis of the solution related to a selected specification of preferences, while the upper panel provides controls to access other functions of the application, such as on-line documentation, contact to the developers, as well as switching analysis to other problems and/or problem instances. Detailed description

[16]The figure shows an example of a small problem. For the actual analysis the panel contains about 60 criteria organized in a hierarchical structure. The meaning of a button is explained as a hint (not shown in the Figure) displayed when the mouse points to a selected button.

of the functionality of the MCA illustrated by tutorial examples is available in the user guide [12].

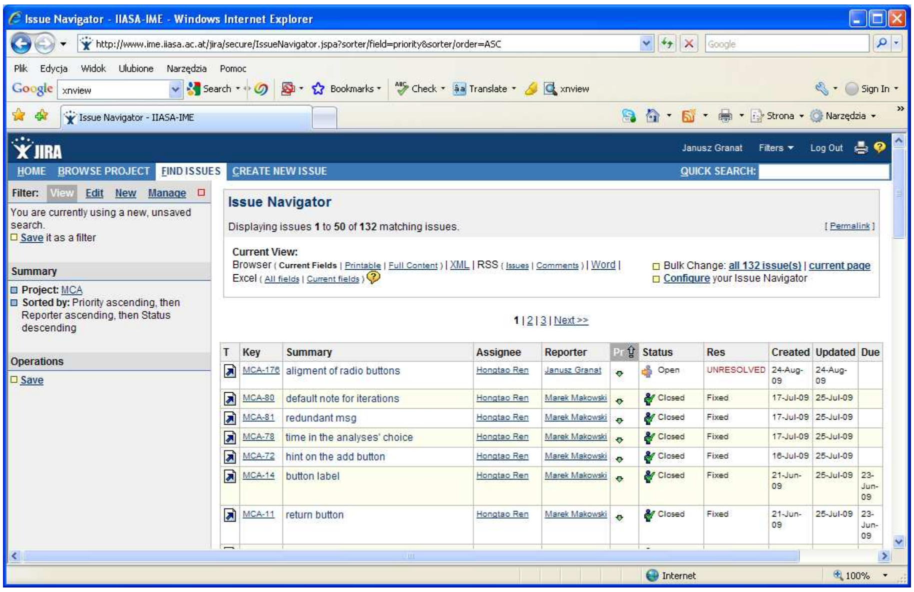

Figure 7: The JIRA screen.

MCA provides the *Contact* utility, an easy to use and effective for users to make suggestions, ask questions and report problems to developers. For organizing the process of problem solving by the MCA developers the JIRA system is used. JIRA is a highly popular and effective bug-tracking, issue tracking and agile project management software application. Each submitted problem has an unique key, short summary, assignments to the person responsible to solve the problem, reporter name, priority, status, and dates of creation, update, due. All submitted problems can be classified in various way, e.g., according to the priorities, due date, types, affected software version, etc., which significantly helps in management of software development.

JIRA also provides an API, therefore it was relatively easy to develop a simple form through which the MCA users can submit a problem description directly to the JIRA. An example of the developer's view on selected problems is shown in Figure 7. Moreover, the application handling the user input also stores all information (like the browser and OS specifications, screen id, and the current status of the analysis) necessary for replicating the situation that was at the time the problem was reported. The latter is of course very helpful in solving the problem and providing the user with an appropriate feedback.

5.4 Summary of the MCA implementation

5.4.1 Versions of the software

There are three versions of the MCA software:

- The version dedicated to the multicriteria analysis of stakeholder preferences done within the NEEDS project. This version had a limited functionality, tuned to the needs of stakeholders who analyzed an assigned problem using a selected method. Therefore, only one (out of four specified for the whole analysis) predefined problem was available for each stakeholder, and one solver was available to all stakeholders. Stakeholders taking part in the analysis were asked to fill-in another survey to provide their profile for the second stage analysis. This version is no longer available.

- The version used for the survey has been enhanced, in particular the user interface and documentation were substantially improved; also access to all four problems is now provided for all users. This enhanced version is now publicly available as the MCA-Needs. It has a dedicated documentation which provides the background and various details on the underlying problems, i.e., future energy technologies in the four European countries: France, Germany, Italy, and Switzerland.
- A general purpose MCA Web-site, which supports analysis of problems defined by the users, as well as several predefined problems provided for testing, and for the tutorial.

The user guide to the MCA is available as [12]. There is an automated self-registration to the MCA and MCA-Needs, which eases their use by anybody interested either in multiple criteria analysis of discrete alternatives, or in such an analysis of future energy technologies. Since the features of the two versions currently available are practically the same, henceforth we use only the MCA name.

5.4.2 Summary of the basic features of the MCA

MCA is Web-based thus providing users with *anytime, anywhere* access. The basic characteristics of the MCA are as follows:

- It has a server-client architecture:
  - ⋆ The server side runs on the Solaris-based computers operated by the IME[17] team. The servers provide all resource-demanding functionality, including handling of data, and running the solvers of the underlying optimization tasks used for selecting Pareto-alternatives corresponding to the specified preferences.
  - ⋆ The *thin-client* side runs on a Web browser selected by the user. Most popular browsers are supported, and no plug-ins are required. The only requirement for the browser is to allow the pop-up windows generated by the IME server.[18]
- The user specifies his/her preferences in a very simple, yet effective way (in the sense of easy analysis of all Pareto-efficient alternatives). After the preferences are specified the solver is called and various characteristics of the solutions (current and previously obtained) are available to the user.
- Each user has his/her own private data space, therefore he/she can specify own problems, their instances, and the corresponding analysis. She/he can interrupt the analysis process, and continue it later.
- There is an on-line tutorial for the MCA, with several pre-loaded problems and their analysis. In this way, the users can become familiar with the MCA without having to start by preparing data for their own problems.
- MCA provides the *Contact* utility, an easy to use and effective tool for users to make suggestions, ask questions, and report problems to the developers.
- There is automated self-registration to the MCA, which allows easy start to use it for anybody interested in multiple criteria analysis of discrete alternatives.

[17] Integrated Modeling Environment Project of IIASA.

[18] Such windows are used only for providing the necessary functionality of the analysis. Of course, they are not used for any type of advertisements.

5.4.3 Summary of the issues specific to the MCA-NEEDS

The research that provided the basis for the development of the MCA-NEEDS focused on developing methods and a Web-based tool for multiple analysis of problems characterized by:

- Two-stage analysis:
  - ⋆ large number of invited stakeholders (about 3000) having diversified backgrounds and interests, as well as typically very limited analytical skills,
  - ⋆ experts analyzing the stakeholder preferences in order to prepare recommendations for future energy technologies.
- Four similar problems (one for each of the four countries), each characterized by:
  - ⋆ a large set of discrete alternatives (over 20),
  - ⋆ a large number of criteria (over 60) organized in hierarchical structure represented by an unbalanced tree,
  - ⋆ a number of criteria having multimodal value distribution and/or either large or very small range of values.
- Easy and effective access through the Web by a large number of users. Most of the users had limited computing and analytical skills; however, some of them had knowledge and experience in multiple criteria analysis.
- An easy way for specification of preferences, suitable for users without analytical skills.

The set of criteria defined was developed by a dedicated research activity. The four sets of alternatives described in Section 2.4 were developed by the NEEDS project participants, then prepared in CSV format files, and uploaded to a data-server. The verified data was prepared for the stakeholder's analysis in the a CSV[19] text format, which was uploaded to a data-server (see Section 4.2). This approach guaranteed that all stakeholders were analyzing the problems defined by the same data set.

The analysis was done independently for four countries (see Section 2 for details), i.e., each of the stakeholders invited to the survey was assigned a specific country. The user had only the choice of the language used for the interface, i.e., either English or German. Moreover, the software version used for the survey had several additional features compared with the two versions currently available, including: two languages for the interface (English and German), and a dedicated introductory video explaining the whole analysis process step-by-step.

6 Experience

6.1 Beyond the state-of-the-art

According to the author's best knowledge, the MCA is the first application for interactive multicriteria analysis that has introduced the following novelties to this type of analysis:

- It is Web-based, i.e., provides *anytime anywhere* access to the analysis. The client-server architecture results in fast interaction; this is achieved by the design in which the thin client handles only the data related to specification of preferences and displaying

[19]The abbreviation comes from: Comma Separated Values. However, another character can be declared as the separators.

the results; the resource-demanding computations and data management are done by servers.
- It uses the database technology for all elements of the modeling process that consists of several stages: the problem definition, the definition of the problem instances, and all elements of analysis of each instance. Data for the whole process is managed by a data server thus allowing subsequent analyses from different physical locations.
- It provides several functions that simplify definition of new problems, their instances, and analyses. The users have a choice of defining new problems by either preparing a csv-format file or by interactive specification of the problem. New problems can also be specified as modifications of the previously defined problems. Several problem instances of a problem (that differ by selection of alternatives and/or attributes used as criteria) can be defined from a problem. Moreover, several analyses (each composed of iterations associated with a specification of preferences) can be done for each instance. Such a hierarchical structure of data and analysis greatly simplifies specification and analysis of non-trivial problems.

6.2 Lessons learned

This multicriteria analysis of a large number of alternatives resulting from multidisciplinary research and done by a large number of stakeholders was the first activity of its kind. Moreover, the MCA is the first Web-based client-server implementation of interactive multicriteria analysis. Therefore it is worthwhile to summarize the lessons that are likely to be of interest for researchers and practitioners.

Here we point out the selected issues we suggest considering when developing applications having requirements similar to those specified in this report:
- Requirement analysis is a critically important (but in practice often forgotten) element of any non-trivial application. It should be done early enough to allow for development of appropriate methods in situations when no appropriate methods and/or tools are available.
- All persistent data of the whole analysis process should be managed by a DBMS.
- The server-client architecture is typical for Web-based applications. A thin client is also typically used; however, one should consider efficient data caching to achieve reasonable performance in situations when the client needs access to even a moderate amount of data.
- Modular structure of the GUI and solvers eases not only software development and maintenance but also experimentation with various ways of preference specification and the corresponding solvers.
- The DBMS used for handling all persistent data (including the problems, preferences, users, and results) should also handle data defining the configuration of interfaces between the application components.
- For two-stage applications (composed of both individual analyses and the analysis of the resulting preferences) it is recommended that user profiles be handled on a different server than the one used for individual analyses. In this way one can more easily assure the privacy of individual preferences, and yet provide aggregated data for the second-stage analysis.
- Contacts with the users can be maintained through an API to bug tracking software

(e.g., JIRA). This is effective in handling comments and problem reports, the latter can be effectively used in software maintenance by linking the reported problems assigned to a developer with a version control system (such as svn) used for software development. A properly configured API should enable easy replication of the reported problem (including information about the client computing environment).

- On-line documentation, including dedicated documentation for specific cases is very useful. Although its development requires substantial resources, it is strongly recommended.
- Automated self-registration and generation of access codes appears to be necessary for efficiently handling a large number of application users.

Finally, we mention two issues that are rather commonly known but still remain typical troublemakers in the development of non-trivial applications. First, the amount of needed resources (especially time) is underestimated. This problem is even more difficult to handle in applications that require input from other activities as delays in providing inputs cause delays in testing the application on actual data. In order to cope with this problem it is recommended to plan in advance the development of realistic approximations of the missed input, and use it for initial testing. Second, the broad version range of external components such as browsers, client operating systems, or DBMS used (or affecting) the developed application result in many unexpected problems; some of them require a substantial amount of resources to detect the problem and its source, and then to fix it.

We close the summary of the experience by stressing the value of collaboration with experts in domains pertinent to the problem, including the substantive area, stakeholder involvement, methods of multicriteria analysis, development of the Web-based GUI's, and DBMS. Collaboration with experienced users willing to test the pre-release version of the application is also essential. A successful development of a complex application is practically impossible without such a wide and diversified network of experienced and dedicated collaborators.

7 Conclusions

The report provides a comprehensive analysis of the requirements for the multicriteria analysis of future energy technologies to be performed by a large number of stakeholders, and summarizes the actual implementation of this analysis.

In the planning stage of the NEEDS project it was assumed that it would be possible to select one of many existing methods and tools for multicriteria analysis of sets of discrete alternatives, and to implement them for a survey of stakeholder preferences. The comparison of the requirements documented in this report with the analysis of features of the available methods documented in [6] clearly shows that new methods for multicriteria analysis had to be developed. Moreover, the requirement analysis has also shown that developing a Web-based interactive application was the only rational way to support actual multicriteria analysis by a large number of stakeholders.

The development of new methods and their pioneering implementation as a Web-site supporting interactive multicriteria analysis required solutions of several methodological and technological problems. These problems and their solutions are also relevant to other applications of science-based support of policy-making. Advances in technology also makes the internet widely available for public participation by citizens in policy-making. Actual participation often involves analysis of conflicting objectives and attainable goals, which is the essence of multicriteria analysis. However, true multicriteria analysis is an interactive process, and its effective support (especially for participants with limited analytical skills) still remains a challenge.

The implementation described in this report shows that meeting the requirements of an effective multicriteria analysis of a complex problem by a large number of diversified stakeholders is possible, but it requires multidisciplinary work throughout the entire process, starting from the requirement analysis, through development of suitable methods and modular tools, and their integration into an application that needs to be supported by skilled staff during its use. Thus the authors believe that the approach and experience described in this report will be useful for researchers and practitioners involved in science-based support of policy-making in various areas.

References

[1] BURGHERR, P., HIRSCHBERG, S., AND CAZZOLI, E. Quantification of risk indicators. Deliverable report RS2b D-7.1, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[2] BURGHERR, P., HIRSCHBERG, S., AND SCHENLER, W. Implementation, evaluation and reporting on the survey on criteria and indicators for assessment of future electricity supply options. Deliverable report RS2b D-12.3, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[3] ELIASSON, B., AND LEE, Y. Y. *Integrated Assessment of Sustainable Energy Systems*. Kluwer Academic Publisher, 2003.

[4] GOLDSTEIN, G., HOBBS, B., AND LAITNER, J. *MARKAL Goal Programming Formulation. MARKAL-GP Version 5.1*. International Resource Group, 2003.

[5] GRANAT, J., AND MAKOWSKI, M. 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).

[6] GRANAT, J., AND MAKOWSKI, M. Multicriteria methodology for the NEEDS project. Interim Report IR-09-10, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2009.

[7] GRANAT, J., MAKOWSKI, M., AND OGRYCZAK, W. Multiple criteria analysis of discrete alternatives with a simple preference specification: Pairwise-outperformance approaches. Interim Report IR-09-23, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2009.

[8] GREENING, L., AND BERNOW, S. Design of coordinated energy and environmental policies: use of multi-criteria decision-making. *Energy Policy 32* (2004), 721–735.

[9] HIRSCHBERG, S., BAUER, C., BURGHERR, P., DONES, R., SCHENLER, W., BACHMANN, T., AND CARRERA, D. G. Sustainability criteria and indicators for assessment of electricity supply options. Deliverable report RS2b D-3.2, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[10] HOBBS, B., AND MEIER, P. *Energy Decisions and the Environment. A Guide to the Use of Multicriteria Methods*. Kluwer Academic Publisher, 2000.

[11] MAKOWSKI, M., GRANAT, J., AND OGRYCZAK, W. Overview of methods implemented in MCA: Multiple criteria analysis of discrete alternatives with a simple preference specification. Interim Report IR-09-24, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2009.

[12] MAKOWSKI, M., GRANAT, J., AND REN, H. User guide to MCA: Multi-criteria analysis of discrete alternatives with a simple preference specification. Interim Report IR-09-22, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2009.

[13] MAKOWSKI, M., GRANAT, J., SCHENLER, W., AND HIRSCHBERG, S. 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).

[14] MESSNER, S., AND STRUBBEGER, M. *User's Guide for MESSAGE III, WP-95-69*. IIASA, Laxenburg, Austria, 2001.

[15] MESSNER, S., STRUBEGGER, M., AND WIERZBICKI, A. Energy planning. In *Model-Based Decision Support Methodology with Environmental Applications*, J. Wessels, M. Makowski, and A. Wierzbicki, Eds., Mathematical Modeling and Applications. Kluwer Academic Publishers, Dordrecht, 2000.

[16] MESSNER, S., STRUBEGGER, M., AND WIERZBICKI, A. Energy planning. In *Model-Based Decision Support Methodology with Environmental Applications*, A. Wierzbicki, M. Makowski, and J. Wessels, Eds., Series: Mathematical Modeling and Applications. Kluwer Academic Publishers, Dordrecht, 2000, pp. 399–414. ISBN 0-7923-6327-2.

[17] NIGIM, K., MUNIER, N., AND GREEN, J. Pre-feasibility mcdm tools to aid communities in prioritizing local viable renewable energy sources. *Renewable Energy 29* (2004), 1775–1791.

[18] POHEKAR, S., AND M.RAMACHANDRAN. Application of multi-criteria decision making to sustainable energy planning, a review. *Renewable and Sustainable Energy 8* (2004), 365–381.

[19] SCHENLER, W., AND BACHMANN, T. Quantification of economic indicators. Deliverable report RS2b D-5.2, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[20] SCHENLER, W., BAUER, C., BURGHERR, P., AND HIRSCHBERG, S. Final report on indicator database for sustainability assessment of advanced electricity supply options. Deliverable report RS2b D-10.1, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[21] SCHENLER, W., HIRSCHBERG, S., BURGHERR, P., MAKOWSKI, M., AND GRANAT, J. Final report on sustainability assessment of advanced electricity supply options. Deliverable report RS2b D-10.2, NEEDS project "New Energy Externalities Developments for Sustainability", Brussels, Belgium, 2009. Available from `http://www.needs-project.org/2009/`.

[22] SIMONS, A., BAUER, C., AND HECK, T. Quantification of environmental indicators. Deliverable report RS2b D-6.1, NEEDS project ”New Energy Externalities Developments for Sustainability”, Brussels, Belgium, 2008. Available from `http://www.needs-project.org/2009/`.

[23] ULUTAS, B. Determination of the appropriate energy policy for Turkey. *Energy 30* (2005), 1146–1161.

A Selected applications of MCDA to energy planning

This appendix contains a review of the state-of-the-art of applying multicriteria analysis to energy problems, as well as characteristics of three applications that exploit different multicriteria analysis methods for energy problems considered relevant to the analysis reported in this paper. Section A.1 provides here a brief overview of applications in the energy planning area, including a brief classification, literature review and discussion and Sections A.2 through A.4 present three selected case examples of prior multicriteria analysis of energy problems.

A.1 Prior MCDA applications in the electric and energy sectors

MCDA has a broad history of use in both the electricity and energy sectors. Both fields offer rich opportunities for a variety of modeling and optimization methodologies. The problems in these fields are complex and multi-dimensional, meaning that modeling or optimizing based on any one criterion (including least cost) is readily seen as overly simplistic. Therefore MCDA has often been applied either as an endogenous optimization function or as a post-analysis method of ranking results. MCDA has typically been used on an ascending scale with three main levels, including the following.

Technology choice: This is typically in the area of generation technology choice for either a generic or specific site. A broad range of criteria apply, but interaction with the rest of the electric system is ignored.

Electricity sector models: Modeling the electricity system means an integrated analysis of how different technologies are combined to meet shifting demand over time. The classic use is system dispatch modeling, which optimizes plant operation based on the variable dispatch cost using either a load duration curve or hourly operation approach. Dispatch modeling may be used tactically over the short term to model operation of an existing system, or for strategic planning over the long term to model system expansion. Some related, subsidiary electricity-related uses of MCDA emphasize the modeling of competitive markets and deregulation, emissions control policies and costs and transmission and distribution. Many electricity models ignore demand-side issues and price feedback on demand.

Energy sector models: Energy models include electricity as one sub-sector of the wider energy sector. They are generally based on a broader, higher level, including

- Substitution between different primary energy resources.
- Specification of end-use technologies with competition/substitution.
- Incorporation of price feedback on demand.
- Aggregation on a national, regional or global level.

Such models may use simulation or optimization over successive time periods, and again the MCDA may be either endogenous to the modeling or exogenously performed upon results.

A.1.1 Literature review

A literature review of MCDA applications was conducted, focusing largely upon electricity and energy related uses within 1) the Swiss research library search service NEBIS, and 2) an online MCDA bibliography database maintained at the University of Auckland in New Zealand.[20] Other reviews of MCDA applications in energy planning were also surveyed, see e.g., [3, 8, 10, 15, 17, 18, 23].

These various sources show that within three main levels of technology, electricity and energy indicated above, MCDA methods have been applied to a wide range of specific topics, including the following areas (the numbers in brackets indicate the number of specific papers surveyed).

Energy sector topics:

- General Energy Planning & Policy (24)
- Project, location or technology specific planning (12)
- Expansion planning (6)
- Emissions related (3)
- Transmission & Distribution (2)
- Deregulation/competition (1)

Electric sector topics:

- Strategic expansion planning (10)
- Dispatch/scheduling (9)
- Transmission & Distribution (7)
- Competition & deregulation (2)
- Emissions reduction (2)

The NEEDS project falls within the area of expansion planning, specifically the choice between many different generation technologies and several different system expansion scenarios, based upon sustainability considerations. As can be seen, papers dealing with expansion planning are a minority of the topics surveyed. The following discussion focuses on describing methods used in expansion planning, or used in related areas and suitable for such use.

The literature review reveals that a primary dichotomy within the area of expansion planning is between those methods that endogenously optimize the choice of technology or scenario, and those methods that choose between discrete or predefined alternatives. The optimizing approach appears more dominant in the literature, but this may be less true in real-world applications as publications may tend to over-represent more theoretical approaches.

A range of mathematical programming techniques has been used for endogenous optimization. Linear programming (LP) and mixed integer-linear programming (MILP) appear to dominate this area, but other methods include various goal-seeking approaches, including distance minimization or aspiration/reservation techniques. It is important to distinguish between the optimization technique involved and the way that the multicriteria approach is formulated into the objective function of the technique. For example, both LP and MILP techniques have a linear formulation of the objective function, which implies a linear tradeoff between the different criteria (the integer restriction of some variables for

[20] `http://www.esc.auckland.ac.nz/people/staff/mehr002/References`.

MILP is part of the constraints and not the objective function). This linear formulation may imply[21] a weighted sum approach to the MCDA; this is often cost minimization with pricing of non-economic criteria, or can be formulated as the weighted sum of expected values or expected utility functions.

The mixed-integer linear programming approach is often chosen because of the integer-number nature of building a new generation facility (i.e., it is impossible, or at least undesirable, to build only part of a new plant).

While it is not generally explicit in the literature, it does appear that for some optimizing techniques (e.g. LP and MILP) the application of the tool (or model) to the energy or electricity sector came first, and the MCDA elements were added later as a way of expanding the tool to incorporate other additional criteria. This is an evolutionary approach to using MCDA. The use of MCDA in the energy and electricity sectors also has trends in development, which include combining different MCDA tools or methods (e.g., Promethee and AHP or the use of fuzzy logic in many different approaches).

Applying multicriteria analysis to a set of discrete options typically aims not only at finding an optimum but also at providing various characteristics of pre-defined alternatives, typically ranking or classification or clustering of alternatives. The literature shows that the weighting approach is very popularly used in the electric sector for discrete rankings, as well as for the optimizing approaches described above. Overall, the weighting approach is fast, easy to understand, and flexible, allowing the incorporation of utility and risk elements. It does have drawbacks however (e.g., eliminating one option may cause the ranking of the remaining options to change). More detailed discussion of the features of the weighting approach is provided in [5].

The other main school of ranking evident in energy applications is the French school, including the family of Electre models (Electre I, II, III and IV, Electre IS and TRI) and Promethee. These models use the twin elements of concordance and discordance (or conjunction and disjunction). The concordance procedure allows a ranking of alternatives based on their positive elements, and the discordance procedure down-rates alternatives that are particularly bad on some (one or more) criteria. The 2D graph produced on the concordance/discordance axes gives a visual representation of which alternatives do well on many criteria and poorly on few, but a definite and unique ranking is not produced. The literature indicates that these models are more frequently used for screening alternatives as acceptable or unacceptable within a hierarchical framework of needs than for a cardinal ranking.

In addition to the concordance/discordance method, several other MCDA screening methods are available, including dominance comparisons, maximin/minimax comparison (risk averse), maximax comparison (risk positive), and lexicographic elimination. These methods are not used to produce cardinal rankings, so while their presence in the literature is noted, they are not suitable to the present NEEDS needs in the electric sector.

[21]This depends on the type of the scalarizing function. For example, reference point approaches use a non-linear scalarizing function, which however can be converted to a linear problem. Therefore an LP/MIP approach does not imply a weighted sum approach.

A.2 CETP (China Energy Technology Program)

Members of the NEEDS Task RS2b team have applied MCDA methods in a number of past projects, but one in particular illustrates the way that several screening and ranking approaches can be used together to provide a richer MCDA perspective. The China Energy Technology Program was a large project that used state-of-the-art techniques to apply sustainability criteria to electricity sector planning in Shandong province, China.

From the electric system modeling perspective, the CETP project consisted of automated, repetitive simulation of electric power system dispatch using a model called EGEAS (Electric Generation Expansion Analysis System). A large number of scenarios (18,144) were defined using stakeholder inputs. Specific alternatives were combined to produce 1008 strategies that were modeled under a range of specific uncertainties producing 18 different futures. Strategies specifying a mix of different new generation technologies were implemented using a model called PSP (Pre-Specified Pathway) to schedule the construction of individual plants. EGEAS was used to simulate least-cost system dispatch to produce plant generation, fuel consumption, plant and system costs and pollution emissions. These results were combined with results from other tasks that modeled life cycle burdens, emissions transport and damages, and risk and safety factors to produce a wide range of sustainability indicators for each scenario. MCDA methods were applied to these results in three main different ways.

A.2.1 Multi-scenario, multi-attribute tradeoff analysis

The repetitive simulation approach applied in CETP does not optimize for the ”best” solution, but rather ”maps out” the option space available. The results are compared using interactive computer graphics to datamine the mass of results produced. In particular, tradeoffs between different pairs of criteria are examined to find patterns due to the effects of specific scenario options and uncertainties. These patterns showed the interactions between old and new capacity, fuel choices and operation alternatives (like early retirement or pollution control retrofits). The same software used for interactive statistics was also used to present the results to stakeholders, emphasizing strategies that were robust and flexible. This was a MCDA screening application that allowed stakeholders to reject dominated strategies and focus upon the tradeoff set of Pareto optimal strategies for key tradeoff pairs, in particular cost v. SO2 emissions.

A.2.2 Concordance/Discordance MCDA analysis using stakeholder preferences

To assist the stakeholder decision-makers participating in these projects, a second phase of MCDA was used for deeper analysis of a subset of 12 selected scenarios. The MCDA concordance/discordance ELECTRE III model was selected for this analysis, and the stakeholder preferences were gathered using individual interviews. The concordance/discordance method did not produce a simple ranking, but rather a 2D mapping of which strategies performed consistently well versus occasionally poorly.

A.2.3 Interactive weighted average MCDA for DVD presentation

The results of the CETP project were published in a book that included an accompanying DVD presenting the project’s structure, assumptions and results. This DVD included presentation of both the screening and Electre methods described above. However for this purpose, a simple method of MCDA was also desired that could be interactively used to elicit preferences and present the user with rankings of individual generation technologies and simple combined strategies. The weighted sum approach was chosen for this purpose, and programmed in Macromedia Flash. This approach required some simplifications of system dispatch, emissions transport and other factors, but it also allowed individual users to experiment and learn about the implications of their own choices.

The experience gained in CETP indicates the strong value of using and comparing more than one method of MCDA analysis. This definitely requires a commitment of time and effort, but it also prevents undue confidence in a single method requiring subjective inputs (as all MCDA methods do).

A.3 MARKAL goal programming formulation

MARKAL is a large energy-economy model that covers the entire energy sector, including the electricity sector. Many different versions of the model exist, with a large user community that employs them for national, regional and global studies involving scenario analysis of energy economics, the environment, etc. MARKAL itself is used to formulate or structure energy questions, and its output passes to a solver engine that actually computes the solution to the stated problem. MARKAL models the full energy sector, including competing primary fuels (coal, oil, gas, uranium, wind, etc.), energy transport and conversion (i.e. primary energy to an energy carrier like synthetic fuels or electricity), and competing end-use technologies that supply energy service demands (for heat, light, transportation, etc.). Although MARKAL models represent the entire energy system, some versions focus in more detail on the electricity sector or other areas like synthetic fuels and transportation. While originally a linear programming model, some formulations of the MARKAL family add non-linear elements and/or demand elasticity.

MARKAL's objective function was originally simple cost minimization, and the cost of emissions constraints were given by shadow prices. MARKAL has been expanded in many cases to consider multiple criteria by adding them to the objective function, implicitly monetizing them (e.g., carbon taxes). However MARKAL can also use an objective function formulation that is goal seeking. This means that rather than putting monetary weights on non-economic factors, the model attempts to minimize the distance in vector space from a given multi-criterion goal state.

A.3.1 The substantive model

The model specification of MARKAL [4] can be summarized by the following set of equations:

$$q_1 = \sum_{t \geq gpstart, e \in GPENV} ((1/cap_{e,t}) * escal_e * (ewt_e^- d_{1e,t}^- + ewt_e^+ d_{1e,t}^+))$$

$$q_2 = \sum_{t \geq gpstart} ((1/least\_cost_e) * cscal_e * (cwt^- d_{2t}^- + cwt^+ d_{2t}^+))$$

$$TSC = \sum_{i,t} c_{i,t} x_{i,t} \epsilon$$

$$\sum_i a_{i,t} x_{i,t} \leq b_t \qquad \forall t$$

$$\sum_{e \in GPENV, j \in F} e_{e,f} x - f, t + d^-_{1e,t} - d^+_{1et} = cap_{e,t} * (1 - cappct_e)$$

$$\sum_i c_{i,t} x_{i,t} + d^-_{2t} - d^+_{2t} = least\_cost_t$$

$$x_i, b_i, d^-_1, d^+_1, d^-_2, d^+_2 \geq 0$$

where:

- $c_{i,t}$ - cost associated with each component or technology i of the energy system for time period t
- $a_{i,t}$ - matrix coefficient associated with each variable and row in LP representation of the energy system
- b_t - the right hand side of the equations of the LP for period t
- $e_{e,f}$ - emission coefficient associated with the technologies/fuel types in the energy system
- $x_{i,t}$ - variables associated with each component of the energy system
- q_1 - shows the total emissions over time,
- q_2 - denotes the total discounted costs over time.
- TSC - defines that the total investment over time must sum to the total cost TSC,

and the remaining equations reflect system structure, emissions and costs.

A.3.2 The preference structure

The preference structure for a single criterion minimization is represented by the objective function s defined as:

$$s = q_1(cap_{e,t}, escal_e, ewt^-_e, ewt^+_e) + q_2(least\_cost_e, escal, cwt^-, cwt^+)$$

with the following given parameters:
$escal_e$ - scaling factor for each emission
$cscal$ - scaling factor for total cost
ewt_e - weighting factor, above/below, for each emission
cwt- weighting factor, above/below, for total cost
$cap_{e,t}$ - emission levels from the reference case
$least\_cost_t$ - cost of least cost solution from the reference case
$gpstart$ - year from which the GP emissions & costs limits are applied

Note that a scaling factor is used to bring the different variables (in different units) to a common scale (0-1 or 0-100), and any variation from the target value for each criterion is penalized by an individual weighting factor, which can be different above and below the target value.

A.4 Reference point method - an energy planning model for Vienna

Energy planning is a general term that is applied to a variety of issues. It can address, for example, the design of energy supply and utilization in new buildings; it can also address municipal planning of district heat supply and the structure of heating systems. In national energy planning, the focus is on political targets such as a diversification of energy sources or environmental targets such as a reduction in acidification of soil and lakes.

The public utility of Vienna used the dynamic linear programming MESSAGE [14] model for its energy plan to evaluate the future development of the municipal energy system, especially with respect to the coordinated expansion of the gas and district heat grids. The organizational structure is such that electricity, district heat, and natural gas are handled by three players in the energy market of Vienna.

A multi-objective approach was natural in the more long-term planning problems of energy systems. The model for Vienna has been set up as a multi-objective optimization model ensuring that three objectives are minimized: system costs; energy imports; and pollutant emissions (using an aggregated index for various pollutants, which is generally applied in Vienna). A simple aggregation of these objectives into one is not possible; for example, although energy imports can be counted as costs, the dependence on imported energy is a separate issue and it is difficult to convert this objective into monetary units; the same concerns pollutant emissions.

A.4.1 The substantive model

The dynamic linear programming model MESSAGE [14]. The variables of MESSAGE were grouped into three categories:

1. Energy flow variables representing an annual energy flow quantity. The unit is usually MWyr for small regions and GWyr for bigger areas
2. Power variables representing the production capacity of a technology (usual unit: MW or GW)
3. Stock-piles representing the quantity of a fuel being cumulated at a certain point in time (usual unit: MWyr or GWyr).

The constraints generated by MESSAGE were grouped into the following categories:

1. Energy flow balances modeling the flow of energy in the energy chain from resource extraction via conversion, transport, distribution up to final utilization
2. sum or relational constraints limiting aggregate activities on an annual or overall basis, either absolute or in relation to other activities,
3. dynamic constraints setting a relation between the activities of two consecutive periods
4. counters that are only used for accounting purposes.

A.4.2 The preference specification

The targets of such investigations differ depending on the scope of the problem and the decision makers involved. Industrial bodies and energy utilities strive for strategies with minimal costs. In this case other objectives, such as environmental or social aspects, are typically viewed as constraints. As an example, fuel use in a power plant can be constrained due to site-specific regulatory emission limits. However, such constraints are actually soft; and their classical representation as hard constraints often results in various difficulties. This was the reason for applying the reference point approach that proved to be a very suitable analysis method for the energy planning in Vienna.

The *Reference Trajectory Optimization Method* is an approach to optimize more than one objective function for a problem in a way that circumvents the necessity of defining weights for converting a multicriteria problem into the corresponding single criterion problem. The reference point approach allows the definition of reference trajectories for all objectives; the solution of the auxiliary parametric optimization problem lies on the Pareto-optimal border of the feasible region and is as close as possible to all reference trajectories.

From a methodological point of view, the results of the study show the usefulness of a multi-objective modeling approach. Especially, the applied reference point approach supports multi-objective problem analysis which proved to be much better than the classical single-criterion optimization-based approaches, including the most popular method of treating multicriteria problems by assigning weights to criteria. More details on this study can be found in [16].