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DECISION MODELLING TOOLS FOR UTILITIES IN THE DEREGULATED ENERGY MARKET

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Title: Decision Modelling Tools for Utilities in the Deregulated Energy Market

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Abstract: This thesis examines the impact of the deregulation of the energy market on decision making and optimisation in utilities and demonstrates how decision support applications can solve specific encountered tasks in this context. The themes of the thesis are presented in different frameworks in order to clarify the complex decision making and optimisation environment where new sources of uncertainties arise due to the convergence of energy markets, globalisation of energy business and increasing competition.

This thesis reflects the changes in the decision making and planning environment of European energy companies during the period from 1995 to 2004. It also follows the development of computational performance and evolution of energy information systems during the same period. Specifically, this thesis consists of studies at several levels of the decision making hierarchy ranging from top-level strategic decision problems to specific optimisation algorithms. On the other hand, the studies also follow the progress of the liberalised energy market from the monopolistic era to the fully competitive market with new trading instruments and issues like emissions trading.

This thesis suggests that there is an increasing need for optimisation and multiple criteria decision making methods, and that new approaches based on the use of operations research are welcome as the deregulation proceeds and uncertainties increase. Technically, the optimisation applications presented are based on Lagrangian relaxation techniques and the dedicated Power Simplex algorithm supplemented with stochastic scenario analysis for decision support, a heuristic method to allocate common benefits and potential losses of coalitions of power companies, and an advanced Branch-and-Bound algorithm to solve efficiently non-convex optimisation problems. The optimisation problems are part of the operational and tactical decision making process that has become very complex in the recent years.

Similarly, strategic decision support has also faced new challenges. This thesis introduces two applications involving multiple criteria decision making methods. The first application explores the decision making problem caused by the introduction of ‘green’ electricity that creates additional value for renewable energy. In this problem the stochastic multi-criteria acceptability analysis method (SMAA) is applied. The second strategic multi-criteria decision making study discusses two different energy-related operations research problems: the elements of risk analysis in the energy field and the evaluation of different choices with a decision support tool accommodating incomplete preference information to help energy companies to select a proper risk management system. The application is based on the rank inclusion in criteria hierarchies (RICH) method.

Keywords: Deregulated energy market, Multi-Criteria Decision Making, Optimisation, Modelling

Academic dissertation
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Decision Modelling Tools for Utilities in the Deregulated Energy Market

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Publications

The dissertation consists of the present summary article and the following papers:

[I] Lahdelma R., Makkonen S., 1996, “Interactive Graphical Object-Oriented Energy Modelling and Optimization”. Proc. of the International Symposium of ECOS’96, Efficiency, Cost, Optimization, Simulation and Environmental Aspects of Energy Systems, June 25-27, Stockholm, Sweden, pp. 425-431.

[II] Makkonen S., Lahdelma R., 1998, “Stochastic Simulation in Risk Analysis of Energy Trade”. In: Steward, van den Honert (Eds.), *Trends in Multicriteria Decision Making, Proc. 13th International Conference on Multiple Criteria Decision Making, Lecture Notes in Economics and Mathematical Sciences (465)*, Springer, Berlin, pp. 146-156.

[III] Makkonen S., Lahdelma R., 2001, “Analysis of Power Pools in the Deregulated Energy Market through Simulation”. *Decision Support Systems 30(3)*, pp. 289-301.

[IV] Makkonen S., Lahdelma R., Asell A.-M., Jokinen A., 2003, “Multi-criteria Decision Support in the Liberalized Energy Market”. *Journal of Multi-Criteria Decision Analysis 12(1)*, pp. 27-42.

[V] Makkonen S., Lahdelma R., 2005, “Non-Convex Power Plant Modelling in Energy Optimisation”. *European Journal of Operational Research*, pp. *XXX-XXX*, to appear (Article in press, Available online 10 March 2005).

[VI] Ojanen O., Makkonen S., Salo A., 2005, “A Multi-Criteria Framework for the Selection of Risk Analysis Methods at Energy Utilities”. International Journal of Risk Assessment and Management 5(1), pp. 16-35.

Contributions of the author

This work has been done at Process Vision Oy (a Finnish IT company) in co-operation with Helsinki University of Technology, University of Jyväskylä and University of Turku.

Papers [I][II][III] and [V] were completed as a part of the EHTO (Electricity and Heat Trade Optimisation) project supported by National Technology Agency of Finland (Tekes). The author was the Director of the project.

In paper [I] the author was the main contributor in setting the problem and in designing the graphical optimisation application. The author was also responsible of a part for the software implementation, testing and experimenting. He was acting also as a secondary author.

In papers [II] and [III], the author was the primary author and the author's contributions were primarily in problem setting and in the implementation and the verification of the application. In paper [V] the author was the primary author, and the author's main contribution was the problem formulation and modelling.

Paper [IV] was part of the GENERIS (General energy information system) project supported by Tekes. The author was the Director of the project and the primary author of paper [IV]. The author developed the framework for the stochastic multi-criteria problem and defined the energy market model.

Paper [VI] is a result of a research project financed by Process Vision Oy. The author was a formulator of the research scope and the secondary author.

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This thesis is the result of 11 years work in the energy information technology industry. During this period many things have changed both in the operating environment of the energy industry, in operations research methods, in the IT sector - and also in my personal life. There have been times when some extra encouragement has been needed to continue the research activity.

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Helsinki, September 2005

Simo Makkonen

1 Introduction

In the past decade, the energy market has been one of the main sectors in the global privatisation trend that aims to improve the efficiency of the previously publicly run activities. Due to its economical, environmental and social impacts and its investment-intensive nature, the energy sector has had a specific role that has attracted the interest of different groups from politicians and authorities to investors, environmental activists, energy intensive industries and even household customers. Consequently, the deregulation of the energy market has been studied intensively (Denton et al. 2001, Newbery 2002). On the other hand, the domestic consumers have not been very active on the competitive market even though in many countries they have been given a freedom to choose their electricity and gas suppliers (European Commission 1999). Also, in many European countries the restructuring process of the energy market has taken much more time than was anticipated. After the competitive businesses were separated from monopolistic grid/network operations, the focus has been in the consolidation of the energy sector rather than in customer level competition (Bower et al. 2001).

Previously the markets for different energy commodities such as oil, gas, electricity and district heating were separated. Today, these markets are converging due to deregulation of the energy business and due to the globalisation of gas and electricity businesses. The green certificate and emissions trading schemes will link the different energy sectors even more closely to each other (Boots 2003). This makes the interactions between the business processes of the different sectors increasingly complex.

The liberalised market needs new models and methods for planning (Dyner and Larsen 2001) because the uncertainty is increasing (Philpott et al. 2000) and the problems become larger. Sahanidis (2004) discusses in length the state-of-the-art of optimisation under uncertainty and many of the ideas presented in his paper are valid also in other areas of the current energy markets. The new liberalised market means also that there are more transactions to process and more data to manage (Roth 2004). Hence, more information needs to be included in the decision making and planning processes and more attention needs to be paid on how to formulate and implement the models efficiently. While the complexity of the problems has increased, the computational power of computers keeps also increasing which allows for more accurate and sophisticated modelling.

The energy sector is one of the core application areas in operations research and decision sciences due to the fact that energy systems are large, require large investments and are technologically challenging to implement (Read 1996). Much of the recent research in the energy field has focused either on the analysis of macro level phenomena, policy studies (Dyner and Larsen 2001, Halseth 1998, Moitre and Rudnick 2000), technology driven research (Sakawa et al. 2002, Tari and Söderström 2002) or micro level analysis i.e. behavioural studies of single customers in order to enhance the competitive status of businesses in energy procurement of domestic customers (Lewis 2002, Loomis and Malm 1999). As a result, plenty of algorithms have been developed for and applied to problems related to energy systems. Also, from the methodology and modelling point of view the deregulated energy market has been a particularly interesting field for operations researchers (Hong and Weng 2000, Carraretto and Lazzaretto 2004, Labadie, 2004, Vlahos et al. 1998). Much less research has been focused in the area of decision support problems of medium-sized energy companies and the published studies have been typically focusing only on a single specific area, for example, the optimal long-term power generation expansion planning problem of an energy company, see e.g. the survey of Kagiannas et al. (2004).

The main purposes of this thesis are: 1) to discuss the effects of the restructuring of the energy market on decision support tasks in the utility level; 2) to describe how the decision support needs are evolving as the deregulation is proceeding; and 3) to present new approaches to help the decision makers (DMs) facing the new problems. We propose that the energy system related operations research needs to be reoriented and refocused to better match the needs of the fast evolving deregulation on the energy market. The papers included in this thesis both chart the changes in the needs of decision support in the strategic and operational level of energy companies and analyse the new methods needed to solve the decision making problems. Most of the applications presented in the separate papers of this thesis relate to the widely used commercial EHTO / GENERIS energy information system that has been developed during the years 1995-2004 - i.e. the time period when the Finnish energy sector transformed from a monopoly to a fully open, competitive market. Thus, this thesis will also reflect the related information technology and software development aspects as they have evolved during the last decade.

The focus of the thesis is in planning and modelling issues of optimisation and decision making problems in energy companies during the transition period from monopoly to full competition. In this setting, we analyse the new needs for decision support tools and seek to answer the following questions: 1) what are the modelling challenges in the different phases of liberalisation; 2) what kind of decision support models are needed; and 3) how can such models be implemented in real-life decision support systems? The conclusions are based on experiences in modelling problems that we have faced during 11 years while working for an IT company providing energy information systems and decision support tools for energy utilities in Northern and Central Europe, New Zealand and Australia.

This thesis consists of an overview and six papers. The modelling and planning examples developed and reported in the papers are based on different fields of operations research. Paper [I] examines optimisation problems of energy utilities applying the Lagrangian relaxation method. Paper [II] extends the deterministic cost minimisation problem to stochastic risk analysis and profit maximization subject to the volatile market price. Paper [II] introduces also a multi-criteria decision aid (MCDA) framework that helps the DM to choose his/her best trading strategy according to his/her risk attitude. In paper [III] the optimisation model of paper [I] is supplemented with an analysis of pool-members' efficiency and with an analysis of different profit/loss sharing methods. Paper [IV] formulates the strategic planning task of a retailer as an MCDM problem and analyses the problem using the stochastic multi-criteria acceptability analysis method (SMAA) (Lahdelma and Salminen 2001) to help the DM to identify the most acceptable decision alternatives from a large set. In paper [V] the optimisation problem introduced in papers [I][II] and [III] is extended with non-convex power plant models that are solved using a dedicated Branch-and-Bound algorithm. Paper [VI] introduces another MCDM application of selecting the risk management system based on the rank inclusion in criteria hierarchies (RICH) method (Salo and Punkka 2005).

This thesis is structured as follows. Section 2 describes the planning, optimisation and decision support problems, Section 3 reviews the separate papers, Section 4 introduces some ideas for future studies in the field, and Section 5 concludes the thesis.

2 Planning, optimisation and decision support in the deregulated energy market

During the period from the early 1990's to the end of 2004 the transition of the energy market has occurred step-wise in Northern Europe (Pineau and Hämäläinen 2000, Brunekreef and Keller 2000) and some other countries, such as, Argentina, Australia, Chile, New Zealand and the USA. In many of the countries the transition has proceeded from the monopolistic era to a fully competitive market. This has had an impact on several business processes in the energy industry (Strecker and Weinhardt 2000, McGovern and Hicks 2004) including decision making and planning tasks (Read 1996, Spinney and Watkins 1996, Vhalos et al. 1998, Larsen and Bunn 1999, Labadie 2004).

In particular, introduction of the competitive market implied that new planning models needed to be implemented for several previously non-existent tasks as risk analysis and optimal bidding (Zhang et al. 2000, Wen and David 2001). On the other hand, the deregulation has also changed traditional planning tasks. For example, long-term power generation planning (Kagiannas et al. 2004) and optimal dispatching (Carraretto and Lazzaretto 2004) have evolved considerably. Similar evolution has also challenged the energy corporate strategic decision making. See e.g. the study of Larsen and Bunn (1999) who describe the changes in modelling in the 1990's at the energy sector and company levels.

Even though deregulation has faced some obstacles and delays in many countries (e.g. Newbery 2002) we have nevertheless seen a major growth in the amount of information that must be managed in daily operations, and the response times in decision making processes have become much shorter than what they used to be (Roth 2004). This gives us a reason to extend the list by Larsen and Bunn (1999) with increased amount of operational information and also to widen the modelling and planning problem with the information management concept. The planning, optimisation and decision support problems can no more be separated from the information they are based on. Many new tasks require the use of information management systems and embedded applications.

2.1 New challenges and needs

The liberalised market needs new models and methods for short-term, medium-term and long-term planning and decision support. Figure 1 illustrates the time scale of different tasks extending from strategic decision making tasks to operational activities of a utility. The time span of the decisions varies widely making the overall decision making process very challenging. Figure 1 also shows the three main decision making levels. The top level considers the impact of deregulation on strategic decision making and investment planning in energy companies. The next level covers the tactical decision making. Here the key issues are the selection of decision making tools for new decision making problems and the creation of new policies, methods, applications and models for decision support and planning problems. The third, operational level, focuses on solving the operational planning and optimisation problems.

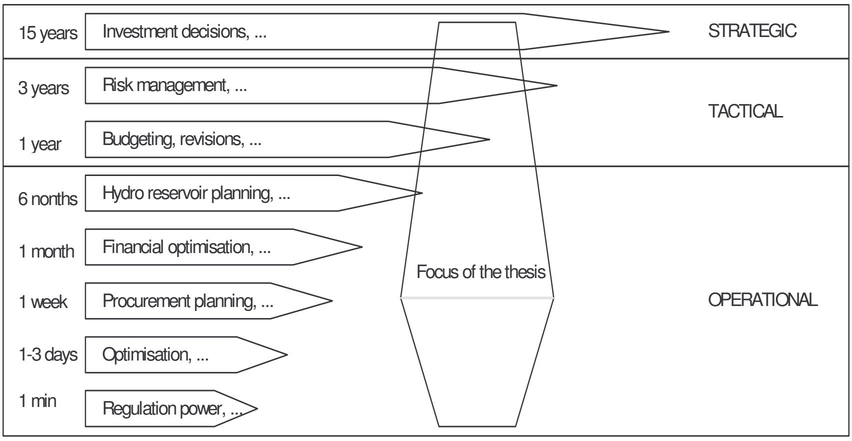

Figure 1. Decision making levels and time span in energy industry

On the other hand, the new tasks can be linked to evolution of the market. Figure 2 illustrates the planning tasks and follows schematically the deregulation process in Finland. It also includes several functions that have been topical during the time they were introduced but which are still in use and are nowadays part of standard business practice. Figure 2 also links the individual papers of this thesis to the different transition phases of the deregulating energy market.

Figure 2 illustrates the most essential steps in the market opening during the analysed time period. In many countries the opening of the market has been a step-wise process starting with legislative changes and then followed by the opening of the market first for wholesale customers, then for industrial and commercial customers able to provide interval metering values and finally also for household customers. In the Nordic countries the deregulation of the electricity market was followed by the introduction of the renewable energy certificate system (RECS) and the European wide emissions trading scheme (ETS). Figure 2 also shows several topics related to the emergence of the market: the establishment of independent system operators (ISO's), focusing in the balance management changes as the new trading principles in the market has been launched; the unbundling of monopolistic network operations and competitive retail operations; the formation of coalitions and cooperatives to reach economies of scale both in retailing and purchasing; separation of the balance responsible operations from the retailing activities; and the formulation of risk policies and risk management systems. These same steps have been taken in several countries during last years, and they have been followed by or companioned with mergers and acquisitions, diversification in sales products and branding with large scale marketing campaigns, as well as introduction of electronic communication protocols (e.g. Electronic Data Interchange for Electricity i.e. EDIEL) between market parties.

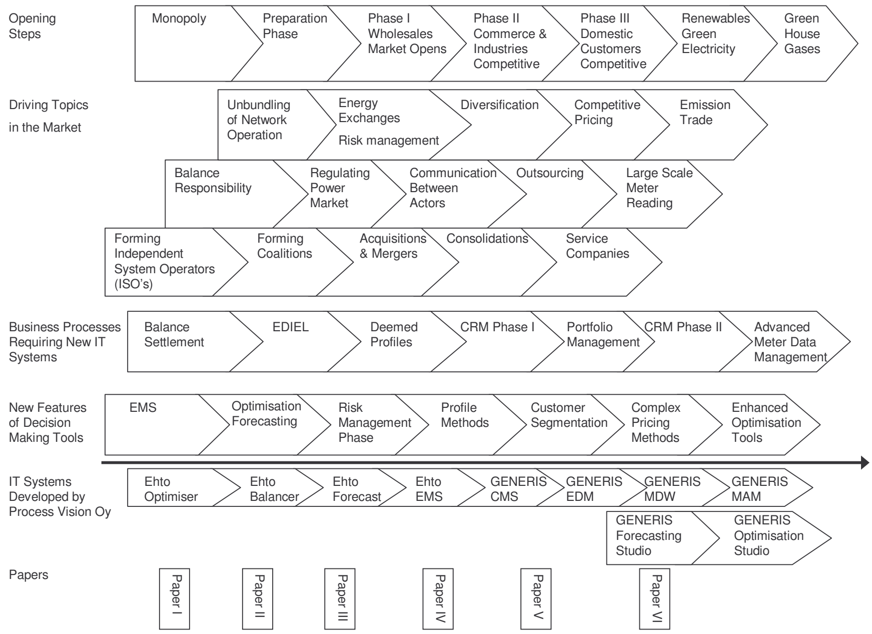

Figure 2. Schematic stepwise opening of the market and the related steps

The changes have also included consolidation of markets, establishment of new service companies and outsourcing of operations like meter reading, billing, metering, risk management and some maintenance and service operations of the assets. The most recent notable developments have been the introduction of emissions trading and large-scale automated meter reading. To summarize the developments we can say that the changes have been revolutionary and impacted the whole industry. The new business principles and practices formed during the deregulation process required clearly more communication between the various market parties and thorough changes in their information infrastructure. It has been necessary to develop new information technological solutions for balance settlement, for communication between parties (e.g. EDIEL), for profiling of non-interval measured customers and also for customer relationship management (CRM). On the other hand, the increasing competition and diversification has dictated a need for new tools to handle new competitive pricing methods with complex product structures (market prices, cap and floor components etc.) and to manage different customer segments and portfolios. This has also impacted the procurement side where the optimal procurement has required enhancement of optimisation and forecasting tools. To sum up the new IT related needs and challenges, we can say that the market can no more operate without automatic information management. The solutions mentioned in Figure 2 are only a sample of the several systems and tools that the new deregulated operating and business environments demand. Figure 2 illustrates some real world solutions to give a more concrete idea of what is needed in a modern energy information management system.

2.2. New planning environment

Traditionally, operational decisions are supported by an energy management system (EMS) while the strategic decision making tools have been more offline-type applications. The traditional EMS tools have aimed to minimise the production costs of a local distribution utility against a given load forecast with utility's own production facilities along with long-term wholesale purchases, a small number of short-term procurement contracts and, if available, spot energy trades. This is no longer sufficient in the deregulated market where end users have the right to purchase energy (electricity or gas) from any supplier. The free competition between the energy suppliers changes the previously 'known' demand profile, and the pricing environment has also become much more dynamic with the introduction of energy exchanges that define the hourly market price for power. This creates a need for active procurement and demand portfolio follow-up and planning. Thus, the new extended EMS must also include specialised tools and mechanisms for planning and managing contract portfolios, spot market trade and financial instruments to be used on the strategic, tactical and operative level.

The increased demand for flexible energy management systems to fulfil the new requirements was identified based on the market analysis at the early phase of the deregulation of the Nordic energy market. The EHTO (Electricity and Heat Trade Optimisation) system was developed during the last half of 90's. EHTO provided upper-level planning services using advanced mathematical modelling, optimisation and data handling. The purpose of EHTO was to serve as the energy manager's tool for supporting the planning of both energy acquisition and sales with versatile contract and trade portfolios. The role of the EHTO Energy Support System as part of the entire energy management infrastructure of an energy company is visualised in Figure 3. The studies presented in this thesis are based on the EHTO system together with some upper-level spreadsheet based simulation and planning tools. The main emphasis is on the operational and tactical decision support tasks although some strategic decision making problems are also discussed.

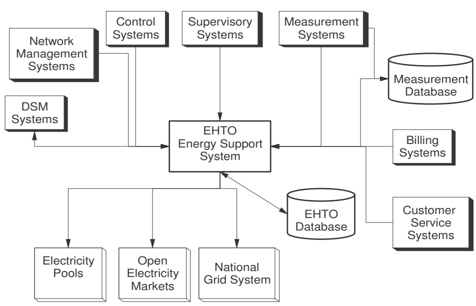

Figure 3. Energy information systems in an energy company

The increasing number of contracts and the possibility for continuous spot market trade require reliable and user-friendly tools supporting economical analysis with abundance of information flowing from on-line measurements. We differentiate the new energy management systems from the earlier ones by calling them energy support systems (ESS), energy information systems (EIS) or in some contexts also energy data management systems (EDMS).

We emphasize that the planning, optimisation and decision making tools should not be evaluated anymore only from the algorithmic point of view but also in terms of the following set of criteria:

1) Configurability
2) Accuracy
3) Performance
4) Usability / Ease of use

These criteria should be taken into consideration when developing the new planning framework for deregulated energy market.

First, the commonly used text-base *configuration* files (e.g. Lahdelma 1994) are not practical in non-trivial modelling applications because the modelling syntax is complex and maintenance is error-prone. We thus argue that the new support systems require interactive graphical model configuration tools integrated with flexible database structures and model definition formalisms separated from algorithm implementations.

Second, the *accuracy* of the model requires more attention than in the past because the modelling environment is more heterogeneous than in the monopoly era. For example, if we optimise a contract portfolio containing both large and small contracts with capacities (capacity limits of e.g. 1000 MW and 1 MW correspondingly) the smaller contracts may be optimised incorrectly due to numerical inaccuracies. We encountered this problem when using the Lagrangian relaxation method for combined heat and power optimisation. As a response we developed later the Power Simplex algorithm and used an extreme point formulation for power characteristics to improve the accuracy solving the hourly models (Lahdelma and Hakonen 2003, Rong and Lahdelma 2004).

Third, the *performance* of real-life applications is also a key criterion as the information to be handled increases and as the decision making cycles become shorter especially on the operational decision making level with spot trading and even regulating power bidding obligations. Thus, there is not anymore time for overnight calculations - the decision support recommendations must be obtained much faster.

Fourth, as the number of users of planning and decision support methods increases due to the deregulation and as the planning tasks are distributed into separate organisational levels, the *usability* issues must be treated as a key criterion when considering a wider employment of the complex optimisation and decision making algorithms.

We can summarize the impact of deregulation to planning, optimisation and decision support by stating that

- there is an increased need for analytical models
- there are more uncertainties present and thus stochastic modelling approaches are needed
- a wider set of problems needs to be solved
- more information must be included in decision making process which requires high performance models
- there are more potential users for the models requiring better usability

In addition, the division between operational, tactical and strategic decision making seems to be getting increasingly relevant in the deregulated energy market where the organisational roles are restructured.

3 Papers

This thesis consists of 6 individual papers. The main ideas, contributions and arguments of the each paper are highlighted in the following sections.

3.1 Optimisation of energy procurement and trade [I]

Paper [I] introduces a new object-oriented optimisation, simulation and planning system equipped with a graphical user interface to configure, operate and monitor the results of the selected optimisation case. The paper describes the needs for a new extended energy management system due to the regulation and introduces the EHTO system for both short-term and long-term energy optimisation and planning. The system architecture is discussed and the graphical model components and user interface principles are presented. Mathematical model components for unit models are defined and these are used for composing an overall planning model. The idea for solving the cost minimisation objective function is based on an object-oriented approach and decomposition of the overall system into several subsystems. To solve the problem, we use the Lagrangian relaxation method. Experimental results using a real-life case are also reported. Performance analyses show that the C++ based object-oriented implementation with interactive graphical user interface was able to reach almost the same optimisation speed as a traditional off-line implementation of the optimisation algorithms.

3.2 Stochastic simulation and risk analysis of energy trade [II]

Paper [II] focuses on the problems of optimal procurement and of the risk assessment given uncertain parameter values. Optimisation algorithms for minimising energy procurement costs are based on the ideas presented in paper [I], but now the model is supplemented with sensitivity analysis for marginal cost calculation and risk analysis based on stochastic simulation of uncertain parameter values. We have also assumed that the main objective of energy companies is the maximisation of their expected net profits while maintaining an acceptable risk level instead of cost minimisation of procurement in terms of deterministic parameters. We then identify four kinds of principal risks in trade and apply Monte Carlo simulation (MCS) for analysing the risks involved in energy trade.

The profitability of purchase and sales contracts in the deterministic model can be analysed using for instance marginal cost analysis and scenarios. Paper [II] first describes the models used in the deterministic case and then considers the uncertainties resulting in a stochastic two-criterion programming problem, where the DM not only wants to maximise the expected profits, but also minimise the risks. Based on solving the overall energy system model, MCS is applied to assess the risks involved with a contract portfolio. The analysis is further extended by using parametric analysis on the MCS model in order to compute the expected profits and risks as a function of the power limit of a particular contract. The parametric information is finally used in contract planning, where the DM can choose the power limit leading to the most preferred profit-risk combination from the Pareto-efficient frontier.

3.3 Energy pool forming and benefit allocation [III]

In paper [III] we introduce the decision making problem of forming coalitions (pools) under the pressure of increasing competition in the market. Deregulation along with more sophisticated metering and accounting technologies makes way for various new types of electricity contracts and derivatives. New contract types and the lowered price level had serious effects on old capacity based long-term contracts that ended up being highly over-priced at the end of 1990's in the Nordic power market. While plenty of the old long-term contracts expired by year 2000, they were gradually being replaced with new energy based contracts, short-term contracts and spot market trade. During the transition phase the actors had the challenging problem of managing very complex portfolios of new and old contracts and some of the companies formed coalitions with each other in order to benefit from the economy of scale and also to participate in the new spot and derivative market more efficiently.

Paper [III] focuses on the problem of benefit allocation as a pool is formed. A key result of the analysis is that in the "Split-the-Savings" and "Split in proportion of energy" strategies the costs are ignored which provides weak incentives for pool members to increase common benefits. The "n-1 analysis" instead includes the cost information and thus motivates the pool members to contribute to pool activities, and it also overcomes the larger pool members' energy domination. Finally, the heuristic "hourly booking" algorithm, which is based on pool's and pool members' valid contract portfolios and spot prices during every hour seems to reflect the market situation well. It also eliminates the possible criticism towards unfair allocation and helps to minimise the overall trading costs when the electricity exchange and market prices are available.

Paper [III] includes also a thorough discussion on different pool operations and raises some critical questions regarding pools that have also active trading operations in addition to the "passive" cost-savings strategy in energy procurement.

3.4 Stochastic decision analysis for an electricity retailer [IV]

The energy trading strategies of retailing companies have changed as the deregulation has proceeded. In Paper [IV] we develop a strategic decision support system for an electricity retailer operating in the liberalised market. We introduce a new approach to understand a new instrument, green certificate, in the energy trade. The green certificates were launched in the European market in 1997 to encourage the use of renewable energy sources (European Commission 1997). Since that a number of different models - both voluntary and obligatory - have been introduced in different countries to mobilise the green certificates (Boots 2003). In our study we clarify to decision making process in a voluntary operating environment and analyse the valuation of green certificates in an energy company's strategy through stochastic simulation.

In its strategic decision making, the retailer needs to evaluate the effects of various simultaneous actions in terms of profitability and other important criteria. The retailer must also understand the uncertainties associated with its operation and be able to manage the associated risks. The decision support system is based on a combination of stochastic simulation and optimisation methods and the SMAA-2 stochastic multicriteria acceptability analysis method (Lahdelma and Salminen, 2001). We have demonstrated the use of the system using a realistic case in the Nordic market. The main contributions of paper [IV] can be divided to two separate classes. First, the simulation framework was developed to model the energy market and the uncertainties. Then, the SMAA was applied to analyse the decision making space.

3.5 Modelling and optimisation of non-convex power plant problems [V]

New production technologies, such as gas turbines, combined heat and power generation, and combined steam and gas cycles are gaining popularity in energy production. At the same time the interest to use the generation capacity most optimally is increasing thanks to the European emissions trading scheme getting activated at the beginning of 2005. The new generation technologies include features that require non-convex models to be solved correctly. On the other hand, the risk analysis through stochastic simulation requires solving a large number of models rapidly. Thus there exists a need for more versatile and efficient decision support tools. The development of these tools was a natural extension to the research studies reported in papers [I][II] and [III].

Paper [V] shows how to extend the convex energy system model to incorporate non-convex power plant models and how to solve the non-convex model efficiently. The paper extends the convex Power Simplex formulation of the model (Lahdelma and Hakonen 2003). This model is sufficient when all model components are convex. However, it allows running non-convex components in the area between the convex sub-areas, which is a physically impossible situation. To handle non-convex components correctly, the overall model is augmented with constraints that disallow plants to operate between two or more areas by defining zero-one variables for each area in each non-convex component.

The decision-problem of a power company is formulated as a large mixed integer programming (MIP) model. To make the model manageable and compatible with the models presented in papers [I][II] and [III] we compose the model hierarchically from modular components. To speed up the optimisation procedure, we decompose the problem into hourly sub-problems, and develop a customised Branch-and-Bound algorithm for solving the sub-problems efficiently. In paper [V] we have also discussed the solution algorithm in detail and presented the pseudo-code for the algorithm.

3.6 Evaluation of multiple choice of risk management methods [VI]

Paper [VI] combines two themes, energy risk analysis and decision making problem. It also applies the Rank Inclusion in Criteria Hierarchies (RICH) method for the evaluation of multiple choices with different criteria.

The increasing competition on the deregulated European energy market forces that the utilities have to pay even more attention to risk management problems. To select a suitable risk management policy is a strategic issue for companies. The rapid changes and high peak prices of electricity on the Scandinavian electricity market in the beginning of 2000's have highlighted the importance of risk management and created a wide discussion whether to invest in in-house management competences within companies or to outsource the risk management to service providers. The own risk management approach requires knowledge and a competence level that might be impossible to reach in full scale in small companies. On the other hand, the experiences from outsourcing have shown that outsourcing does not decrease the responsibility of the management to understand and to take care of the consequences of all risk related decisions. This new situation has created a need for re-evaluation of the risk management policies in several companies. One core question in this rethinking is to decide the most suitable approach to risk management and to select the correct risk analysis system to support the risk management targets. In the case study, the evaluation framework was applied using the RICH multi-criteria decision making method. As one of the methods for dealing with incomplete preference information in hierarchical weighting models, RICH allows the DM to associate a set of possible rankings with a given set of attributes.

Our main contributions lie in developing a framework for mapping key concerns in risk policy and risk strategy into requirements for a risk management system. Specifically, building upon experiences from an actual case study, we focus on the decision problem of a utility that is about to implement an IT system for risk management. This system can provide risk information through different risk analysis methods, whereby the costs and benefits of individual methods may be difficult to assess.

3.7 Positioning of the papers

To clarify the needs and problems of the deregulated energy market and to present the related solutions, the individual papers of the thesis can be positioned in different frameworks. The themes presented in the papers focus on problems that appear especially in medium-size energy companies due to the deregulation process. The focus of the thesis is in the optimisation and multi-criteria decision support problems. Many relevant themes like forecasting, risk analysis, investment planning, customer segmentation, optimal bidding etc., which are of wide interest in the energy market have been intentionally omitted.

First, we can position the papers based on the methods being covered and problems being addressed. The individual papers discussing operational and strategic planning as well as simulation, optimisation and modelling issues can be classified as presented in Table 1.

Table 1. Problems and methodologies covered in the separate papers of the thesis

Problem addressed	User	Method	Paper
Optimal energy procurement/generation plan as the market evolves	Operation Management	Optimisation	I,II,II,V
Optimal risk policy and selection of product/pricing strategy based on stochastic simulation	Strategy	Simulation	II,IV
Strategic choice of business coalition and/or business branch	Strategy	Decision Analysis	III,IV
Selection of corporate energy risk management tools	Strategy	Decision Analysis	VI

Second, we can create a framework to answer how the themes are handled as decision support tasks on different decision making levels. Table 2 shows the core themes, the main users and time horizons.

Table 2. Decision making level and core themes

Core themes	How the themes are handled as a decision support task	Decision making level	Paper
Application to optimise procurement costs and an efficient solver for optimisation problem	The cost minimisation problem of an energy producer is solved with an efficient convex-model paper [I] that is extended in paper [V] to non-convex models.	**Operation Actions** Time horizon: 1 hour – a few months Users: Operation Management	I,V
Tactical decision making and planning	The uncertainties in energy price and volume are embedded into a	**Operation Actions** Time horizon: 1 month – 3	II

during the transition phase	stochastic simulation framework.	years Users: Operation management	
Tactical decision making and planning during the transition phase	The benefits and potential losses of an energy pool are allocated using an optimisation model, a heuristic algorithm and n-1 – analysis.	**Operation Actions** Time horizon: 1 month – 3 years Users: Operation management	III
Strategic decision making in energy company	The simulation framework for evaluating the marketing strategy is introduced and the decision making is supported with the SMAA method.	**Business Actions** Time horizon: 1 – 15 years Users: Top management	IV
Selection of decision making tools in energy company	The selection of a risk management system is formulated as a multi-criteria problem and the RICH method is used to solve the problem.	**Strategy** Time horizon: 1 – 5 years Users: Top management	VI

The operations research methods introduced describe the changing decision making environment from three viewpoints. First, the traditional procurement optimisation is solved with three different approaches in papers [I][II] and [V] as the problem setting has changed along with the market needs. The quick change of the needs has been a natural phenomenon since the beginning of deregulation. Second, the decision support approaches introduced in [IV] and [VI] represent only a snapshot of the new challenges of the variety of decision making problems arisen due to deregulation. The two approaches, SMAA and RICH, also show that there is a possibility to successfully apply different new methods to real life problems and to learn more about these phenomena. Third, there are several time spans in the energy companies' decision making. Papers [I][II][III] and [V] discuss mainly the operations and tactical planning problems of a utility. On the other hand papers [IV] and [VI] are more focused on the strategic DM problems.

3.8 Contribution to related fields

There are several issues in which the scientific contribution of this thesis is disclosed. The papers presented in the thesis introduce the following new results:

- Introduction of efficient real-life application using Lagrangian relaxation and Power Simplex. Examination of standard vs. dedicated linear programming algorithms. [I][II]
- Presentation of a new graphical object oriented system to define complex energy optimisation models. [I][II][V]
- Extension of the deterministic optimisation model into risk analysis with stochastic simulation. [II]
- Introduction of a heuristic model for the allocation of pool benefits in the middle of the deregulation process when old long-term contracts are still present and the new spot and financial markets are available. [III]
- Introduction of a new decision support system using the SMAA methodology. In addition, introduction of a new application area for SMAA. [IV]
- Extension of Power Simplex model with mixed integer programming (MIP) algorithm to overcome the non-convexities of power plant characteristics. [V]
- Development of a systematic framework for understanding the key criteria for selection of risk analysis methods. In addition, introduction of a new application area for RICH. [VI]

The main operations research topics covered in the thesis are optimisation and multi-criteria decision making.

3.8.1 Optimisation

The optimisation of energy procurement and trade has been one of the most interesting topics in operations research since the introduction of linear programming (LP) methods (Taha 1997, Rau 2003). A large share of different energy optimisation problems is linear by nature. However, LP techniques can be applied to convex non-linear problems as well, because these can be approximated by piece-wise linear models. To solve non-convex problems, the LP-based optimisation tools were enhanced by introducing a MIP technology. In the late 80's the problems to be solved stayed similar due to the fact that the energy sector was monopolistic and there was no special pressure from the business point of view to develop optimisation techniques and practices.

During the beginning of 1990's, the performance/cost ratio of computers was growing rapidly. This created new possibilities to develop large-scale energy system models for dynamic problems and allowed including to the systems realistic models for hydropower systems with water reservoirs (Philpott et al. 2000) and other energy systems such as heat storages (Bos et al. 1996). Coinciding with this development the Lagrangian relaxation technique was introduced to successfully solve problems such as optimal bidding to independent system operators and optimal scheduling of energy production (Guan et al. 1995, Wang et al. 1995) and the generalised unit commitment problem (Guan and Luh 1992, Baldick 1995). Based on such promising experimental results, we implemented the Lagrangian relaxation algorithm to optimise the one-year optimal procurement of an energy supplier with combined heat and power production. The Lagrangian principle was used both for decomposing the long-term problem into hourly problems and to separate the different acquisition components into component-specific models. We applied the long-term model for many different tasks, such as procurement planning, long-term contract planning and pricing and also extended the model into aggregated hydropower and energy package optimisation.

The joint planning of combined heat and electric power systems is studied also in (Gardner and Rogers 1997), in which the joint-planning problem of combined heat and power (CHP) and electric systems in policy making is discussed. The Lagrangian relaxation method with several augmentations has also been used widely in energy planning since 1995 (Bos et al. 1996, Takriti et al. 2001, Cerisola and Ramos 2002, Chen et al. 2004). With certain CHP/co-generation problems we found convergence problems while using the Lagrangian relaxation method. Therefore, it was later replaced with the dedicated Power Simplex algorithm (Lahdelma and Hakonen 2003) to solve the hourly models utilising the special model structure. The basic ideas of paper [I] were further developed to solve an industrial power generation problem using parametric analysis and the so-called Black Box principle. The Power Simplex method was also later extended in several ways. The Extended Power Simplex algorithm (EPS; Rong et al. 2006) manages several heat balances instead of one. The Tri-Commodity Simplex (TCS) can be used to solve efficiently tri-generation problems (for example, electricity, heat and steam) (Rong and Lahdelma 2005). In paper [V] we extended the modelling and optimisation scope into non-convex power plant problems.

Our own system used standard personal computers, which made it possible to use optimisation models widely in medium-sized energy companies. The main modelling contribution of paper [I] was to extend the Lagrangian relaxation method to the CHP problem and to use microcomputers in solving the annual model efficiently. Regarding the performance criterion in paper [I] the solution time using Lagrangian relaxation technique is roughly proportional to I*T, where I is the number of subsystems and T the number of time periods. This was a remarkable benefit at that time, as the optimisation horizon was one year i.e. 8760 hourly time steps. In the reported case study, the solution time of 8760 steps was about 3 seconds with a low-end microcomputer. In paper [V] we demonstrated the use of the MIP model with a real-life application and compared the performance of the dedicated Branch-and-Bound algorithm using different generation configuration. The results show that the non-convex models take much more time to solve than their convex variants. The largest model takes some 70 times more CPU time to solve than the corresponding convex model. With smaller models the difference decreases but remains significant. This is consistent with the theoretically exponential time complexity of the non-convex models in relation to the number of non-convex power plants and areas. Despite the exponential complexity characteristics, the performance of the modelling and solution technique is applicable to real-life needs.

To summarise shortly the main contributions of the papers in the field of optimisation we first point out that paper [I] describes the early edge of deregulation. At that time the presented EHTO Optimiser application represented a state-of-the-art solution for procurement optimisation. The computer systems were not yet developed enough to handle the changing procurement portfolios; instead these functions were more or less hard-coded or configured with ASCII configuration files (e.g. Lahdelma 1994). Thus, one contribution of paper [I] was to present a graphical tool for creating and configuring the optimisation models efficiently in order to respond to the rapid changes in the surrounding procurement environment. The developed EHTO tool supported also what-if-analysis, and due to its high usability and flexible user interface in model configuration and operation, the EHTO system proved out to be a powerful tool for different kinds of energy system optimisation tasks, as shown in papers [I][II][III] and [V]. The other contribution of paper [I] and successive papers [II][III] and [V] is that they present powerful optimisation applications and methods to support planning of the energy procurement. We showed that the Lagrangian and Power Simplex methods can be used in various real world applications utilizing standard PC environment and that such applications are useful in middle-sized energy companies.

3.8.2 Multi-criteria decision making

MCDM tools have been applied to energy and environmental problems widely because all criteria cannot be easily monetizated. Plenty of literature has been published in this field (e.g. Hobbs and Meier 2000). In Diakoulaki et al. (2005) the current state of art in applying MCDA methods in energy planning is discussed including the technical, social, environmental and economic aspects. The method selection issues and problem classification are also pointed out in the article. In our studies, we found also that some of the MCDM methods could help the DMs in the deregulated market. We further studied several different methods and applied these methods to selected newly emerged problems. In the field of multi-criteria decision making, our main contributions lie in applying the different operations research methods to the new problems in utility sector and in setting-up and formulating these problems into frameworks complying with related model structures [II][IV][VI].

The first MCDM extension to the EHTO system was a 2-criterion case of “risk vs. profit” which was solved by stochastic simulation and a parametric analysis as presented in paper [II]. In paper [II] we discussed the challenge of using this approach in real life and we found that the form of a Pareto frontier is quite sensitive to the selection of the stochastic variables and therefore the analysis of the sensitivity and correlation of the stochastic parameters must be done carefully. In addition, some reasoning about the selection and definition of these variables is needed before an overall acceptance of the method for industrial usage can be made. In practice, visualisation of the results of the stochastic simulation and parametric analysis was found to be important.

The motivation behind the second MCDM application reported in paper [IV] was to enable the retailer to co-ordinate the use of several new instruments in order to maximize profit, to manage the market risks, and to reach other important business goals. At the operative level, the company maximises profit subject to the guidelines from the strategic level. At the strategic level, the DMs consisting of the managerial board of the company choose the product portfolio, pricing, growth strategy, risk-attitude, and other long-term goals. Ideally, all these factors should be represented in the MCDM model. A factor that is particularly difficult to model is the response of the competitors. One way to consider the competitors is to observe their actions and apply strategic planning repetitively on a continuous basis. The system we developed is based on co-ordinated simulation, optimisation and analysis models.

The core of the system in paper [IV] is a deterministic operative optimisation model that defines the different acquisition and sales contracts of the retailer during a single time period. Successive single-period models are linked together with dynamic constraints to form an operative multi-period model that spans through the planning horizon. With fixed values for strategic decision variables and environmental parameters, the operative multi-period model determines the optimal way to utilize the contracts and computes deterministic values for the criteria and other quantities of interest. The decision problem is inherently continuous, but it is discretised by defining different decision alternatives as value combinations of multiple simultaneous strategic decision variables. Each decision alternative is evaluated by using the simulation model. The alternatives are then compared by using the SMAA-2 MCDM method. SMAA-2 classifies the alternatives into efficient and inefficient ones and analyses their overall acceptability subject to different preferences. The analysis can be performed either with or without preference information. The DMs can use the SMAA-2 results for eliminating inefficient alternatives, finding the most acceptable alternatives, and choosing the most preferred alternative from among these. The SMAA-2 MCDM approach for energy field is further studied in (Lahdelma et al. 2003, Lahdelma et al. 2004a, Lahdelma et al. 2004b, Lahdelma et al. 2004c).

The third MCDM application describes the problem of finding appropriate risk analysis methods for a utility as discussed in paper [VI]. Choices among alternative methods involve tradeoffs between the quality and usability of risk information (e.g. relevance, timeliness, accuracy and comprehensiveness) and the costs of (i) implementing, (ii) introducing, (iii) using and (iv) maintaining these methods in the system. For example, raising the quantity and quality of relevant risk information leads to higher costs, but may nevertheless lead to lower total expected costs since risk information helps to mitigate adverse events. In the case study we used the Rank Inclusion in Criteria Hierarchies (RICH) method to evaluate multiple choices in terms of different criteria. The development of a suitable evaluation framework turned out to be challenging in practice. We further found out that the alternative methods and their associated risk measures are rarely commensurate. There are also several subjective attributes – such as those related to utility of information – that are important but often difficult to assess.

As a summary about the use of MCDM we can conclude that the DMs have a central role in the decision support systems. The DMs should participate already in the definition of the decision variables and the related criteria, and they should also understand and approve the different sub-models and their parameters. The final decision is always made by the DMs anyway, not by the decision support system.

4 Future research topics

According to Larsen and Bunn (1999) the deregulation has changed the debate regarding the basic formulation of mathematical modelling from large scale linear and mixed integer problems to stochastic models with several sources of uncertainties - conditions for which the deterministic modelling is a rather powerless approach. We made similar observations, and in the Nordic market the introduction of the electricity exchange has changed the formulation of mathematical modelling even further, because the market price can be used as a reference to decompose many of the previously combined large-scale models. This provides a possibility to concentrate on more detailed modelling in the unit level. On the other hand, the European-wide CO_2 emissions trading, the growing concern over environmental matters, the energy savings incentives, the ever proceeding consolidation of the energy market and the increasing competition in the marketplace are requiring more efficient utilisation of generation facilities. In this framework, there are still a lot of issues to be studied, and in the energy optimisation field the potential future challenges are 1) to combine the stochastic approaches with dynamic systems such as hydropower reservoirs and river-systems, heat accumulators, the CO_2 emissions trading process (Rong et al. 2004) and the large-scale CHP production; 2) to link the strategic, tactical and operational models flexibly together as the amount of information to be managed keeps increasing; 3) to provide reliable and coherent optimisation results to support different levels of decision making; and 4) regarding the optimisation methods, to apply the extended Power Simplex, tri-generation and non-convex models to an overall industrial framework.

In the MCDM environment there are several interesting topics to be discussed and further studied. Based on the results of this thesis and many other articles, it is clear that the future problems are more stochastic by nature and include multiple criteria. The challenge is, however, how the use of MCDM applications could be widened also for the operative level and how the senior and middle level management of the utilities can be convinced to use the MCDM applications. In this context, the potential problems that prevent a wider use of the methods are that 1) there are possible biases in using MCDM models (Pöyhönen 1998); 2) in many cases the chosen multi-criteria modelling approach selected will influence results and the conclusions made; 3) the use of the MCDM requires reflective and time consuming analysis and 4) the results must, in many cases, be interpreted by an expert. Thus, it could be interesting to study whether MCDM methods could become an everyday tool in energy organisations, what are the key issues that should be improved to enhance the use of MDCM, and also how the different MCDM methods, for example RICH and SMAA and their extensions ‘solve’ the same problem - i.e. do they provide same or similar proposals for decision support. In addition, in order to use MCDM methods more widely in industry, special concern must be paid on overall robustness of the methods, data and solutions. Thus, one interesting further research topic is to apply the methodological ideas of robust MCDA to energy decision aid (Rosenhead et al. 1972, Vincke 1999, Dias et al. 2002, Rosenhead 2002, Roy 2003, Sayin 2005, Hites 2005).

5 Concluding remarks

This thesis discusses the decision support and optimisation needs and related planning methods associated with the liberalisation of the energy market in Northern Europe focusing on several specific novel issues faced in the decision making processes of a deregulated utility. The emphasis has been in a pragmatic approach, and consequently the developed theoretical methods have been usable in practical implementations and real-life applications.

The discussion reflects the decision making issues in the transitional phase of restructuring energy markets. Several new needs and problems that utilities have encountered due to the deregulation are presented. First, the change from cost minimisation to profit maximisation is introduced. Second, the change from optimisation against given demand curve to optimisation against given market price is discussed. Third, the change from deterministic and static to stochastic and dynamic modelling is introduced. And fourth, the central role of risk management as a part of the new market dynamics is analysed and discussed.

The energy market has encountered remarkable changes that have affected also the decision making environment. The monopolistic era where deterministic approaches were applicable has given way to an era of uncertainty where stochastic approaches are needed to handle the surprises and fluctuations of the environment. The nature and focus of the decision making problems has kept changing as the deregulation process has proceeded. Earlier the typical decision making challenges were whether and when to allocate a major power plant or a grid line investment financed by the public sector, monopolistic utilities or giant industries. Now there are plenty of new market-driven challenges like risk hedging, customer segmentation or the optimisation of portfolio including new derivatives. Also new financial instruments like green certificates or emissions trading instruments are subject to similar uncertainties. These require several new risk measures and risk management approaches that are discussed in this thesis.

This thesis covers a wide range of topics ranging from algorithms to IT systems and their user-friendliness, from data validation issues to information management challenges, from macro to micro level problems, from technology-oriented to market-driven approaches in decision making, from deterministic to stochastic approaches and from investment related decision making to customer segmentation and multi-commodity driven decision making. In principle, to solve all these new needs and challenges, several different types of modelling approaches need to be evaluated. This thesis presents a solution that provides reasonable practical results for every encountered problem. This does not mean that the presented solution for a specific new problem is the only solution, but it shows that by formulating the problem as an operations research problem and by applying a mathematical model we can learn more about the problem and we can provide adequate support tools for DMs in different positions to solve new problems. On the other hand, medium-sized energy companies have rather limited resources, and in some cases also lack of competence to handle new modelling tasks. This provides a constraint of its own for model development and maintenance. As demonstrated through this thesis, this creates a natural need for dedicated commercial solutions for new decision making tasks.

The new energy and environmental policies have opened new challenges that need both top-level strategic tools and operational tools. The decision making problems can thus be divided into top-level problems where spreadsheets are still usable (Rau 2003) and to operative problems where more advanced information management is in key role. Due to the deregulation principles themselves, due to the increasing number of market players exchanging information with each other and due to an expanding number of supplier switches, the number of information sources and the amount of information to be managed has increased radically. Thus, from the experience in implementing the applications, we have concluded that 1) there is a need for several types of modelling and planning tools depending on the problem and 2) the tools and solutions should be evaluated with several new criteria, e.g. configurability, maintainability, transparency, efficiency and accuracy.

On the other hand, due to the increasing amount of relevant information, pre- and post-processing of information before and after it is used in decision making and model development is becoming more and more important and quality of data may impact significantly to the results of planning models. Therefore, even more emphasis should be placed on information management and data validation while the previous key role of the models and algorithms is diminishing. In the operative tasks the model and the related algorithms are still important but even there information management, heuristic solutions, usability, robustness, accuracy and traceability are becoming more and more important. From this it follows that some main topics of operations research are “moved” from the purely algorithmic domain to information management and embedded solutions dedicated to the problem context. Traditional operations research has thus encountered a hidden revolution that is fuelled not only by new algorithms but also by new information management methods and infrastructures.

The thesis shows that deregulation has not only changed the energy market but that it has also changed the environment where operations research is studied and applied. Many operational issues have been too easily omitted in operations research studies, although the operational challenges play an increasingly significant role in the current businesses. This changed landscape can be expected to affect modelling and operations research methods and to widen the field of operations research also in the future.

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