Project proposal: Model-Based Decision-Making for Large-Scale Systems

Objectives

The main objectives of the proposal are:

- To lay the foundations for improved design and operation of large-scale systems. This will be achieved primarily through i) improving the coordination between different layers of the decision-making hierarchy, and ii) ensuring consistency between the models used at different layers in the hierarchy.
- To educate 7 PhDs and offer 6 man-years of postdoctoral training.

Background

A fundamental problem-solving technique in science and engineering is to decompose problems of unmanageable size and complexity into smaller sub-problems, which are manageable and amenable to systematic problem solving tools. Modern society has many systems and structures of such size, complexity and geographical distribution that this decomposition approach to system design and operation is unavoidable. Some examples include

- Electric power generation, transmission and distribution, with high voltage transmission networks spanning entire continents, generating capacity at a number of points in the network, generation based on wind, hydroelectric power, fossil or nuclear fuels, and low voltage distribution to a very high number of customers.
- Natural gas production, processing, transmission and distribution also spans thousands of kilometres from petroleum reservoirs to a large number of domestic and industrial customers.
- Supply chains for industrial production can similarly span much of the globe, involving a diversity of decision points both in time and space concerning raw material supplies, transportation, storage, processing, and supplying the market with finished product.

A common factor for all such systems is that the sheer scales of the systems make centralized, simultaneous decision making infeasible. The three examples above also share the aspect that in addition to supplying the commodity in question, be it electric power or some industrial product, the systems must also respond to changes in the marketplace. This project will focus on methodology for design and operation of industrial supply chains, but many of the generic problem areas will have their counterpart also in other types of large-scale systems. Figure 1 illustrates the decision-making hierarchies for design and operation of industrial supply chains.

Let us first consider the decision –making hierarchy involved in industrial system operations. The supply chain optimization layer focuses on what products to produce, and the time and location where the products shall be produced. This layer will coordinate production at several production sites, possibly also across international borders, and works on a time scale from weeks to months. This optimization requires information on market prices and demands for products, price and availability of raw materials, available stock and location of goods, available production and transportation capacity, etc. The regulatory control layer, on the other hand, uses plant measurements to determine how to manipulate plant inputs on a time scale from milliseconds to a few seconds, and its purpose is to keep production conditions at specifications, in order to maintain safety, quality and production efficiency.

A single production plant may have some 10 000 regulatory control loops, and the number of points where human intervention is possible will be of similar magnitude. Even with another half century of continued increase in computing power one really cannot foresee that this hierarchical decision-making structure will be replaced by centralized, simultaneous decision making for an entire supply chain. Firstly, the problems often decompose along the time component (for example strategic, tactical and operational horizons). Secondly the problems decompose over borders of processes, departments, divisions and companies. In both cases the overall system will be subject to sub-optimal operation, and the purpose of this project is to investigate and reduce these effects of time decomposition and decentralization

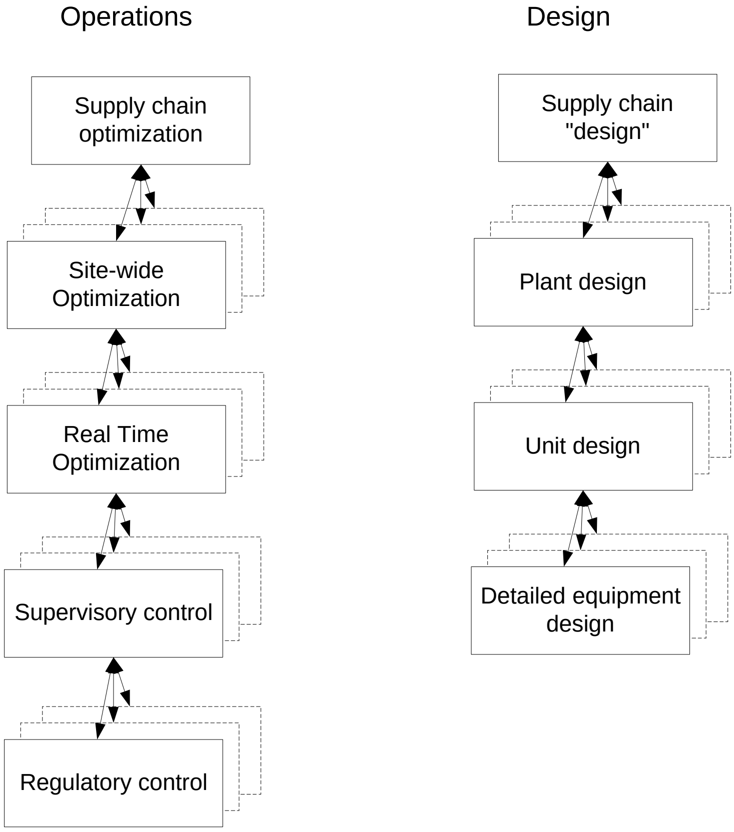

Fig. 1. Industrial decision-making hierarchies

A great advantage of the hierarchical decision-making, and the separation in time scale and geographical scale between the different layers, is that it enables simpler models to be applied on all levels. This advantage may in practice outweigh the drawback of imperfect coordination between the layers. Some of the layers in the decision-making hierarchy may in the future merge, but nevertheless a hierarchical decision-making structure is likely to remain even if constraints in computing power are removed. Thus, the design of the interfaces between the layers in the decision-making hierarchy is a critical issue to avoid sub-optimal decisions. As an example, consider the strategic design decisions for a processing plant. To be able to prioritize in this time horizon, it is essential to know the characteristics of the installed equipment both when it comes to operational control in the regulatory layer and for capacity balancing at the operational scheduling layer. This illustrates the importance of maintaining *consistency* between the models used at different layers in the hierarchy.

Unfortunately, very little work has been done on integrating the planning hierarchy with the layers from real time optimization and downwards. Understanding this interface and its influence on plans and control is an important topic, as the planning layer often sees several processes in connection and seeks to find the optimal co-ordination between them, while the control layer will focus on control of single processes. The final results may depend on which variables are fixed through planning and which are managed in the control system of the individual processes. We seek to increase the understanding of this both in design and operation of the planning system and in process control.

The hierarchical decision-making structure in process operations is discussed and described in more detail in Skogestad and Postlethwaite (2) from a process control tradition, while the planning hierarchy is treated in the seminal work by Anthony (1).

On the design side of Fig. 1, there is a similar division into layers, and similar difference in scale and level of model detail at different layers. The supply chain "design" layer is where the main investment decisions are made, and the focus here is on market demand, storage, production and transportation capacities, etc. The detailed equipment design, on the other hand, may well deal with phenomena on a microscopic scale, and involve highly complex chemical and physical models. Problems involving molecular design focus on even smaller length scales. In the same way as for operations, the decision-making hierarchy for design is also critically dependent on consistency of models used at the different layers of the hierarchy. Modelling and model management therefore becomes vital aspects of effective and reliable decision making in the design and operation of industrial systems.

However, models – however accurate – are of little use on their own (except possibly in education). Only when models are used for making decisions can they improve the design or operation of a system. Frequently, models are used to support human decision making, and focus is then typically on simulations and presentation of simulation results. Although the human brain is very impressive in many ways, it is hardly designed for solving the many complex problems in industrial system design and operation. Aspects of industrial design and operational problems that make them ill-suited for human decision making include

- The required speed of response, which may be down to fractions of a second.
- The repetitive nature of the problems, which would be tiring for a human.
- The sheer complexity of the problems considered

Thus, tools for automated decision-making are required, and such tools do of course exist and are in use in industrial systems. Although some of the decisions are made using simple algorithms, like the ubiquitous PID controller in regulatory control, more complex decision-making typically involve the solution of optimization problems.

Each of the application areas identified with boxes in Fig. 1 has its own set of tools for problem solving and decision-making. Although the quality and relevance of the tools vary between the areas, it is nevertheless fair to say that in general the tools for any given area is better than the quality of the communication and coordination between the different layers. Suppliers of automation equipment may claim to cover all the levels on the operations side of Fig. 1. Although industrial information systems often are capable at documentation, product tracking, etc., they are not satisfactory as systems for hierarchical decision making, due to inappropriate communication and lacking coordination between the layers. Similarly, on the design side it is difficult to accurately communicate requirements, constraints and opportunities between the different layers. This is to some extent unavoidable, due to the different model resolutions at different layers, but there is nevertheless scope for significant improvements in the communication between the layers.

Research needs and obstacles

Contrary to popular perception, even the traditional branches of industry are knowledge intensive, and do perform and support research. However, there is a strong trend to concentrate only on core technology. Thus, industrial companies tend to leave the operational decision-making systems to automation suppliers and engineering or business consultancies. Similarly, on the design side the industrial companies focus on the equipment or unit designs in which their core technology lies. Overall plant design is left to engineering consultancies, with a strong focus on engineering standards, off-the-shelf equipment and experience from previous designs.

Automation suppliers have been successful in adapting developments in information and communication technology to automation systems, and thereby provide much of the infrastructure and information required for implementing a decentralized and hierarchical decision-making system. Due to the large production rates in the traditional industries, even modest improvements in design or operation will have significant economic and/or environmental impact. Within each of the layers in Fig. 1, there is significant and relevant research taking place, which is supported both by public and industrial funds. *However, research on the formulation and solution of decision-making problems at different layers of the hierarchy, relationships between problem formulations at different layers of the hierarchy, etc., has been absent from the industrial research agenda. This is apparently caused by a feeling that the issues involved are not sufficiently well understood to enable short-term payback on the research. Developments in computing in general, and modelling tools and numerical optimization in particular, make hierarchical decision-making systems for industrial production a timely topic for research. The aim of the current research proposal is to break new ground in this area, and lay the foundations of a methodology for the formulation and solution of decision-making problems that accounts for the hierarchical nature of the system.*

Progress in developing methodology for the hierarchical decision–making depicted in Fig. 1 is hampered by the fact that different layers of the hierarchy lie within the realms of different cultures. The lower levels of both hierarchies are dominated by an engineering culture, whereas the higher levels are dominated by a business culture. Each of these cultures generally lacks respect and appreciation of the other, and many have been the discussions about ‘who is more important’. Within the context of the decision-making hierarchy of Fig. 1, such a discussion is irrelevant: The purpose of a lower layer is undefined without input from the higher layers, whereas the higher layers are totally dependent on the lower layers in order to capture any potential for improved design or operation. To ensure a more complete understanding of the issues in question at all layers of the decision-making hierarchy, the proposed project will include personnel from both economics and engineering backgrounds.

Scientific focus of the project

Model-Based Decision-Making in Large-Scale Systems is a huge problem area. Within this area, the project will therefore focus on two research themes, in order to enable effective cooperation and ensure sufficient effort and manpower to make significant progress within each of the chosen research themes. These research themes are:

- Modelling and model management
- Handling uncertainty in hierarchical decision-making

In the following, more specific research issues within these two themes will be described.

Modelling and model management.
Decision-making at any of the layers in the hierarchies depicted in Fig.1 requires the use of a model of the system in question (although the model may not be explicitly formulated in the case of regulatory control). The industrial practice in modelling, and research needs in the area are studied by Foss et al (ref. 5). Models used in **plant operations** and plant design are qualitatively different. Plant design typically focuses on optimality in terms of economy, energy and raw material usage, for a pre-defined set of operational scenaria. For the operational problems, on the other hand, the **plant design** can be considered as fixed, and focus is on maintaining optimal operation in the face of disturbances, changing market conditions, etc. To some extent it is possible to include operational considerations into plant design problems. However, it is difficult to encapsulate all the practical considerations related to plant operations into a plant design problem. Furthermore, even incorporating only a subset of relevant operational considerations in plant design formulations results in very complex optimization problems where it is difficult to understand how the details in the problem formulation affect the optimal solution. Thus, it is important to be able to easily develop models appropriate for analysis of plant operations from the results of plant design problems. The ability of developing a hierarchy of models is equally important, as on every level for each of the different type of tasks (design, operations, etc.) different aspects of the plant are highlighted. Ideally the higher level models should include instances of the lower level decision problems, and it should be possible within the framework to ensure consistency in the data, all the way from the lower layers and all the way up to the strategic decisions. In this setting, models higher up in the hierarchy will constrain and guide decisions on the lower levels, and models at the lower levels are important to predict the effect of decisions made on higher layers to get the correct input and constraints for the decision space.

Many of the decision-making problems encountered in design and/or operation of large-scale systems are formulated as highly complex optimization problems, as for example the Mixed Integer Non-Linear Programming (MINLP) problems most frequently encountered in plant design. With such problems, the way in which the system is modelled affects the ease with which solutions can be found. Research is needed to obtain deeper understanding of how models are formulated in order to ensure that the optimization problems can be solved with relative ease. In addition, considering the different scales in time and space addressed by different layers in the decision-making hierarchy, methodology for deriving models of the relevant scope and required accuracy are therefore needed, as well as methodology for ensuring consistency between the models applied at different layers of the hierarchies. The modelling should be independent of the particular design, simulation or optimization program in which the models are subsequently used. Starting from a unified system description, the modelling methodology should result in models reflecting the scales in time and space that are of interest to the problem at hand, and should be able to model both continuous systems and systems including discrete variables and events.

A new generation of modelling tools is emerging, which approach modelling on a higher level of abstraction, enable a shift of the focus from problem solving, where the current and past focus was placed, to model handling, manipulation and formulation. This approach enables teamwork as models are completely documented and self-standing. Such modelling tools enable the construction of libraries of consistent models for different types of decision-making applications, and decouples the modelling from the application-specific decision-making problem formulation and solution. A prototype of such a general modelling tool exists in project consortium. The project will further develop this modelling tool (the Modeller by Preisig and Westerweele, (ref. 6)). It currently generates simulation models with outputs to several standard simulator environments, and can be extended to generate models also for other programs used for model-based decision-making. The Modeller will thus enable the project to establish a test bed for modelling and model handling across multiple levels of decision-making hierarchies.

Methods have been developed to handle time-scale assumptions in the modeling tool explicitly, to consecutively eliminate the resulting mathematical problems (index problems) through model reduction and to generate discrete-event dynamic models by adding a qualitative discretisation of the state yielding qualitative models. The latter are essential for the planning and scheduling. These results shall be integrated with the modelling tool.

Handling uncertainty in hierarchical decision-making

Uncertainties in large-scale production systems arise from several different sources:

- Uncertainty with respect to future market demand and market prices. This type of uncertainty is typically dealt with at the production planning and supply chain optimization layers.
- Uncertainty due to external disturbances in the production process (e.g., waves on an oil production ship, ambient temperature for air-cooled heat exchanges, etc.). This type of uncertainty is dealt with primarily by the supervisory and regulatory control layers, but may well affect production capacity and thus influence production planning.
- Uncertainty resulting from inaccurate models, arising either from deliberate model simplifications at higher levels in the decision-making hierarchy, or due to unacceptable cost or time required to obtain more accurate models. This type of uncertainty exists at all levels of the decision-making hierarchy.
- Uncertainty due to wear, fouling, catalyst deactivation, corrosion, etc., that may be reduced by appropriate maintenance, but only at considerable cost. This type of

uncertainty affects multiple layers in the decision-making hierarchy, both control and production planning.

Understanding how to account for and handle uncertainty is therefore of great importance to large-scale production systems. Within a single layer of the decision-making hierarchy, there often exist tools for handling uncertainty, e.g., stochastic optimization in production planning and robust control in the control layers. Within the field of supply chain optimization there is an increasing focus on how to handle uncertainty in the coordination of the chain (see for example Escudero, Garcia, Gomez and Sabau (ref. 7) or Tomasgard & Høeg (ref. 8)). Still most research does not consider the issue of linking the different parts of the supply chain, but rather addresses separate parts of the chain. This is essential, since local opimization at each layer may actually destroy global optimality, unless the local optimization problems are formulated to ensure effective cooperation between the various parts of the chain. How to ensure effective cooperation is poorly understood. Furthermore, there is not much done on how to account for and minimize the effects of uncertainties in other layers in order to achieve close to optimal design or operation. In stochastic programming, long term uncertainty is modelled through dynamic scenarios in event trees, and mathematical programming modes makes contingent plans in the scenarios. Such procedures allows for decision flexibility in the plans, and thereby leads to plans that recognize already when a decision is made the possibility to be able to change this a s more information becomes known. There is reason to believe that external uncertainty and the flexible decisions used to deal with it may influence the shorter term decision-making. Thus, important aspects in the handling of uncertainty include:

- What information needs to be transmitted between layers in order to minimize the effects of uncertainty, and how information is aggregated at one layer in order to be effectively utilized at higher layers.
- What type of decision flexibility should be designed into the system to reduce the effects of uncertainty, both in terms of external uncertainty and the internal uncertainty of the process.
- How and whether a system should be actively excited to enable learning about the system and thus reduce uncertainty.
- How specifications that are sent to lower layers are formulated in order to achieve robustness w.r.t. uncertainty at the lower layers.
- How lower layers can adapt their specifications in order to benefit from the more detailed information that is available at the lower layers.

Project consortium and organisation

The project consortium will consist of participants from four different Faculties at NTNU, as is consistent with the wide research area addressed by the project. The principal investigators are listed in Table 1.

Principal investigators	Department / Faculty
Prof. S. Skogestad Prof. H. Preisig Prof. H. Svendsen	Department of Chemical Engineering / Faculty of Natural Sciences and Technology
Prof. B. Nygreen Assoc. Prof. A. Tomasgaard	Department of Industrial Economics and Technology Management / Faculty of Social Sciences and Technology Management

Prof. T. Gundersen Prof. O. Bolland	Department of Energy and Process Engineering / Faculty of Engineering Science and Technology
Prof. B. Foss Prof. M. Hovd (project manager)	Engineering Cybernetics Department / Faculty of Information Technology, Mathematics and Electrical Engineering

Table 1. Principal investigators in the project.

The project will build on established interdisciplinary research cooperation through the Systems Group within the Gas Technology Center NTNU-SINTEF. The Systems Group was established in 2002 following the award of the Strategic University Programme *Process Systems Engineering – From Natural Gas to Energy Products*. In addition to the people already involved in the Systems Group, this project will also include the Applied Economics and Optimization group at the Department of Industrial Economics and Technology Management. Another distinguishing feature relative to existing research cooperation is that this project will focus on generic technologies for decision-making in large scale industrial production systems, rather than applied research within a specific industrial sector. The well-functioning cooperation on existing research is clearly an excellent basis for cooperation in a new project. The project management will be handled with a low level of bureaucracy. A project steering committee will be established with one member from each participating department, in addition to the project manager. The main tasks of the steering committee will be

- to oversee scientific progress and direction within the project,
- to allocate funds for PhD and Post Doctoral students in accordance with the research objectives described above, and
- to allocate additional funds to stimulate high scientific productivity.

To further ensure research cooperation within the project consortium, all PhD candidates shall have a primary supervisor and a co-supervisor coming from different Faculties at NTNU. The project manager will handle the day-to-day running of the project, communication and reporting to the research council, etc.

Scientific quality of the project consortium.

The participants in the project have a proven track record in research and as research supervisors. Table 2 below lists the key scientific production figures for the researchers involved in the project (i.e. *not* the entire departments) for the period 1994 - 2004. Both the Process Cybernetics group at the Engineering Cybernetics Department and the Process Systems Engineering group at the Department of Chemical Engineering have both been rated as excellent by international review panels appointed by the Norwegian Research Council (refs. 3 and 4, respectively). The groups in Industrial Economics and in Energy and Process Engineering have not been evaluated by Research Council panels. However, their academic records are convincing, as documented by their CV's and publication lists (included as an attachment to this proposal).

Category Group	Gradu-ated Dr. Ing. /PhD	On-going PhD	Current post-docs	Journal Papers & Book chapters	Conf. papers w/rev.	Books	On-going EU projects[1]	Marie Curie training site
Engineering Cybernetics	14	8	2	36	65	1	1	0
Chemical Engineering	35	21	3	132	175	2	3	2
Energy and Process Engineering	3	9	3	19	21	0	2	0
Industrial Economics	2	4	1	15	4	0	0	0

Table 2. Key scientific production figures for the project participants for the period 1994 - 2004.

International research and cooperation

The participants in the project have an extensive international network These contacts are too numerous to list here, but is to some extent documented by the many publications with international co-authors listed in the bibliographies of the principal investigators. Participation in EU-funded research (c.f. Table 2) has resulted in active cooperation with many of the leading Universities in Europe within our area. In 2002, the project manager was appointed by the Computer Aided Process Engineering (CAPE) Forum of the European Federation of Chemical Engineering as coordinator and main author of an Expression of Interest (EoI) for the EU 6th Framework Programme. The EoI, entitled ARTeMIS, was supported by 20 commercial companies and 16 European universities. In the present project, the main international collaborators will be

- The Department of Chemical Engineering at Carnegie Mellon University in Pittsburgh, USA.
- The Centre for Process Systems Engineering at Imperial College, London.
- Institute of Mathematics, Brno University of Technology, Brno, Czech Republic.

The collaborators are international leaders in their fields, and cover most of the fields of relevance to the project, including modelling, simulation, optimization, design and control. The collaboration will involve exchange of PhD’s and PostDocs, shorter term visits by senior personnel, as well as joint research projects and publications.

Synergies with ongoing and planned research

There is potential for significant synergies within the project itself, as the project will approach decision making from both the engineering and economic viewpoints, for the purposes of both optimal design and optimal operation. Synergies can be expected also from participation in applied research. The participants in the project are already involved in a number of research projects of a more applied nature within the problem areas depicted in Fig. 1, and are also involved in several other current research proposals. Exposure to applied research projects will provide

- problem definitions and specifications that the technologies developed in the proposed project must accommodate, and
- relevant case studies for testing out the new technologies.

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[1] Not including Marie Curie training sites/research training networks

However, there is no project or project proposal with a similar holistic approach to decision-making in large-scale industrial systems, nor projects aiming at developing generic technologies for model-based decision-making in large-scale systems. Instead, each applied research project focuses on only one or two of the problem areas in Fig. 1, and the needs of a particular industry. Advances can be expected both as a direct result of the research within the project, but also from generalising and leveraging approaches that have found success in individual application areas within industrial decision-making systems.

The proposed project will also make a key contribution to maintaining the level of activity in the research groups involved. Several of the projects that have funded the research groups are approaching their end. Continued high publication rates and education of doctoral candidates will require continued funding.

Dissemination

The results of the project will be published in journals and at conferences. The aim is to publish a minimum of 20 papers in leading international journals, and 30 presentations with papers at international conferences with review.

Dissemination nationally will occur through the extensive networks of the principal investigators. Through the Gas Technology Research Center NTNU-SINTEF, the project consortium has contact with most of the main players on a national level both in industry and in research. These contacts can contribute to further develop the results of the project and incorporate the results in industrial practice. Further dissemination on the national level will occur through the Norwegian research bulletin *Modeling, Identification and Control*, where the project manager is editor.

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