Cost-Effective Industrial Energy Systems

Multiperiod Optimization of Operating Strategies and Structural Choices

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Abstract

It is of great importance to encourage the development of cost-effective industrial energy systems as the potential for saving energy and capital in industrial applications often is substantial.

The MIND method has been developed for multi-period cost optimization of industrial energy systems. The optimal operating strategy of the industrial utility and production systems in co-operation can be found. Existing equipment units can be represented as well as new equipment structures. The representation of process units is performed in a way that facilitates the analysis of processes from various industrial branches. The production processes can be represented at the desired level of accuracy, i.e. one modelling unit may represent an equipment or a whole process line. Parts of the process system may then be represented with a higher accuracy. Since both energy and material flows are included, the interaction between the utility system and the production system can be studied. Nonlinear relations, found in expressions of energy demand, energy conversion efficiency and investment cost, are linearized in mixed-integer linear programming. A flexible time scale facilitates the performance of long and short term analyses. The optional time scale allows variations in boundary and process conditions to be represented.

The MIND method has been applied to several industrial energy systems. The optimal operating strategy of a pulp and paper mill and a refinery showed opportunities of considerable capital savings. In the case of the refinery, possibilities for energy recovery measures, calculated by Pinch Technology, were also included in the optimization. Calculations show that MIND can be combined with other analysis methods and that the combination yields new insights in the total energy system.
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Finally, I want to express my deepest gratitude to Stefan, my beloved husband, for his sympathy and encouragement during this work. I dedicate this thesis to him and our dear son, Andreas.

Linköping in August 1993

Katarina Nilsson
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In this thesis, the introduction and the literature survey of related work are followed by a description of the method and a chapter of comments to the enclosed papers. The following papers are included and will be referred to in the text (I - VI):

(I) Nilsson, K. and Söderström, M.

"MIND optimization reduces the system cost at a Refinery", Accepted for publication in Energy - The International Journal, 1993.
(III) Nilsson, K. and Söderström, M.
"Industrial applications of production planning with optimal electricity demand",

(IV) Nilsson, K.
"Industrial production planning with optimal electricity cost",

(V) Nilsson, K. and Sundén, B.
"A combined method for the thermal and structural design of industrial energy systems",
*Recent Advances in Heat Transfer* (Eds. B. Sundén and A. Zukauskas),

(VI) Nilsson, K. and Sundén, B.
"Optimizing a Refinery using the Pinch Technology and the MIND method",
Accepted for publication in *Heat Recovery Systems & CHP*, 1993.
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NOMENCLATURE

Variables are distinguished from input data by *italics*.
(The nomenclature of the enclosed Papers may differ from this list)

\[ B1 \] Part of the total material flow defining slope 1 of an energy function
\[ B2 \] Part of the total material flow defining slope 2 of an energy function
\[ BP \] Break-point between two consecutive pieces of a linearized curve
\[ c \] Cost, exponent indicates the kind of cost, indexes indicate time step and identification number of flow or node, kr/kg, kr/kWh, kr/kW
\[ cin, cin \] Investment cost, kr/capacity
\[ cin2 \] Investment cost applied at expansion of capacity, kr/capacity
\[ constant \] Integer constant
\[ E \] Electricity flow, kWh/h
\[ effcoe \] Efficiency coefficient
\[ F \] Fuel flow, kg/h, m³/h, kWh/h
\[ fuelcon \] Fuel conversion factor, kWh/m³, kWh/kg
\[ FW \] 0/1 binary variable, indicates a cost related to the existence of a fuel flow
\[ hj \] The number of hours included in the short term time step \( j \), h
\[ IB1 \] 0/1 binary variable, indicates a step in energy demand functions
\[ IB2 \] 0/1 binary variable, indicates a step or ordering of pieces in energy demand functions (related to variable \( B2 \))
\[ IF \] 0/1 binary variable, indicates ordering of pieces in fuel-steam conversion functions (related to variable \( SS \))
\[ IFA \] 0/1 binary variable, indicates a step in fuel-electricity conversion functions
\[ IN \] 0/1 binary variable, related to investment cost
\[ IN2 \] 0/1 binary variable, related to investment cost, representing an expansion of equipment capacity
\[ i \] Long term time step
\[ I \] Total number of long term time steps
\[ j \] Short term time step
\[ J \] Total number of short term time steps
\[ k \] Branch in the node network
\[ K \] Total number of branches in the node network
\[ ke \] Electricity input flow, number of
\[ KE \] Total number of electricity input flows
\[ kf \] Fuel input flow, number of
\( KF \) \hspace{1cm} \text{Total number of fuel input flows}

\( kin \) \hspace{1cm} \text{Flow indicating the existence of an investment cost in the subsequent node, number of}

\( KIN \) \hspace{1cm} \text{Total number of flows indicating the existence of an investment cost in the subsequent node}

\( km \) \hspace{1cm} \text{Material input flow, number of}

\( KM \) \hspace{1cm} \text{Total number of material input flows}

\( ksi \) \hspace{1cm} \text{Steam output flow that generates income to the system, number of}

\( KSI \) \hspace{1cm} \text{Total number of steam output flows that generate income to the system}

\( M \) \hspace{1cm} \text{Material flow, kg/h}

\( MC \) \hspace{1cm} \text{Largest material flow through a node during any time step, kg/h}

\( n \) \hspace{1cm} \text{Node number}

\( N \) \hspace{1cm} \text{Total number of nodes}

\( p \) \hspace{1cm} \text{Number of short term time steps, where electricity peak demand is charged}

\( P \) \hspace{1cm} \text{Electricity peak demand, kWh/h}

\( PE \) \hspace{1cm} \text{Sum variable for output electricity from a steam conversion node}

\( PF \) \hspace{1cm} \text{Sum variable for output steam or heat from a fuel conversion node}

\( PM \) \hspace{1cm} \text{Sum variable of material flow through a process node}

\( PS \) \hspace{1cm} \text{Sum variable for steam or heat from a distribution or aggregation node}

\( S \) \hspace{1cm} \text{Steam flow, kWh/h}

\( SA \) \hspace{1cm} \text{Part of the total steam flow defining slope 1 of an energy function}

\( SS \) \hspace{1cm} \text{Part of the total steam flow defining slope 2 of an energy function}

\( \text{slope} \) \hspace{1cm} \text{The slope of a function, } \Delta y/\Delta x

\( \text{slope 1} \) \hspace{1cm} \text{The slope of the first piece of a function}

\( \text{slope 2} \) \hspace{1cm} \text{The slope of the second piece of a function}

\( \text{ST1} \) \hspace{1cm} \text{End of step 1 (value of the x-axis) in a stepwise function}

\( \text{step} \) \hspace{1cm} \text{Value that specifies a step in a function}

\( \text{step 1} \) \hspace{1cm} \text{Value that specifies the first step of a function}

\( \text{step 2} \) \hspace{1cm} \text{Value that specifies the second step of a function}
1. INTRODUCTION

Industrial energy systems embrace a wide variety of equipment units and plant specific system requirements which form a complex reality.

In industrial energy systems analysis, it is important to define the boundaries of the energy system and to include aspects likely to influence the analysis. The main force for imposing changes in industrial plants is economical savings. Depending on the purpose of the analysis, different parts of the industrial energy system may be emphasized, but the overall requirement is to include the total system, i.e. the process system, the utility system, possibilities of energy recovery and other demands, such as heating of industrial premises. In doing so, the internal flexibility of the system must be expressed as well as variations in boundary conditions.

The flexibility of the processes and the interconnection of the production flows and the energy flows are essential aspects. Technical improvement can be represented as a choice of different process technologies or retrofit measures. When an analysis is made on apparatus level, non-linear relationships will appear. Non-linear constraints may refer to investment cost functions or thermodynamical changes, i.e. efficiency of energy conversion or process energy demand expressed as a function of equipment capacity. The analysis of a non-linear industrial energy system should not be performed in linear terms. Even when only a few equipment units deviate from linearity in the energy demand the result of an economical analysis may be affected as is shown by Nilsson, Söderström and Karlsson (1989).

The production demand and the costs for energy and raw materials are typical boundary conditions in the industrial energy system. Often several kinds of energy can be chosen, e.g. electricity, steam or various fuels. The optimal mix of utility choices and utility operation will influence the total system cost. The choice or combination of raw materials may influence the performance of the production processes. Then the raw material costs and the relation of the material flow to other parts of the industrial energy system are significant. The energy demand is related to the production level and this relation is often non-linear. When external energy demands are served by industrial utilities, they must be included in the optimization separated from the process related energy demand. In Sweden, where the climate varies widely over the seasons, the energy demand is also influenced by climatic conditions.

Some of the conditions mentioned above are time dependent, which is one of the most important issues to consider in an industrial energy systems analysis. The ability to include events in an accurate time scale makes it possible to represent the flexibility of the production processes and the production demand, as well as the
changes of the boundary conditions. This requires a time scale adjustable to the specific requirements of the studied industrial case.

When an optimal structure or optimal operating conditions are sought in an industrial energy system, the optimal conditions are not obvious. It is difficult to foresee the optimal interconnection of the variables in the system without an optimization tool. The development of the MIND method has been performed with an account taken to these issues.

1.1 Hypothesis

It is possible to find new structural and operational solutions by least cost optimization of industrial energy systems. A general mathematical method can be used to represent the dynamics of the system at optional level of representation and with sufficient accuracy of non-linear relations.

1.2 Aims and intentions

The method of mixed-integer linear programming is chosen for the cost optimization. The possibility to use binary integers in the representation of non-linear relations is significant when industrial energy systems are analyzed. A flexible time division will allow for the representation of changes in the boundary conditions as well as the flexibility of the production system, i.e. optimization of the production level and the representation of semi-continuous processes and batch processes. Changes in the production processes may affect the performance of the total energy system, i.e. the material flow, the energy demand, the industrial utility system etc. The interconnection between energy and material flows is accordingly required in the representation of the energy system. A general way of modelling various equipment units implies that the accuracy level can be chosen. It is then possible to increase the accuracy in parts of the system and to reduce the accuracy in other parts. This renders a flexible optimization tool where the variation of modelling problems, found in industry, can be managed. The aims of the industrial energy systems analysis are:

- to make optimal improvements in the existing equipment and new options of process techniques, retrofit measures, and to choose the time of investment.
to find an optimal operating strategy for the industrial energy supply system, i.e. the utility system, and the process system in co-operation, where existing equipment units and restricting bounds are defined.

- to investigate the consequences occurring when changes are introduced in the operating conditions of the industrial energy system or its boundary conditions.

- to combine the strategies mentioned above with other methods of calculation in order to improve the industrial analysis.

The intentions brought forward in the development of the MIND method are briefly described below.

In Nilsson, Söderström and Karlsson (1989) and Nilsson (1990), optimization of operating strategy and choice of equipment structure is described. Equipment units were chosen from parallel options, where existing equipment could be compared to other process techniques, equipment sizes, and choices of time of investment. The results showed that it was advantageous to alter the production schedule between time periods in accord with the electricity tariff. The optimal time of investment and equipment size could be found and that improved the possibilities to shift the production between time periods in conjunction with an increasing production demand.

**Paper I** deals with optimization of the operating strategy in a pulp and paper mill, where existing equipment units have been considered. The significance of a simultaneous multi-period optimization of the industrial utility and process systems in co-operation was shown. The industrial steam production was influenced by the mix of raw materials, i.e. wood and recycled fibres, whereas the on-site electricity production was influenced by the external electricity price, fuel prices and the process steam demand. The optimal choice of utility units in operation, and optimal operating conditions, could be found for each period of the calculation.

**Paper II** also describes the optimization of operating strategy in the environment of existing equipment units. The case studied is a refinery, where the representation of the nonlinear operating conditions of a backpressure turbine, working with and without pass-out steam, is described. The optimal operation of the turbine depends on fuel prices, possibilities of selling heat to the municipal district-heating system, the process demand for electricity and steam, and the process recovery of heat. Without the MIND method, the nonlinear complexity of the system and the flexibility of the boundary conditions would imply a difficult task in predicting the optimal operation of the turbine and other utility units.
Paper III is a study of how to plan the production to reach the optimal electricity demand, when nonlinear demands and differentiated tariffs are represented in cooperation. The consequences of alterations in boundary and process conditions were investigated by changes of input data to the MIND method. The optimal electricity demand is found for three industrial cases, with nonlinear demand functions and for two electricity tariffs.

Paper IV is similar to the study in Paper III. Three cases of electricity demand functions were investigated in conjunction with the electricity tariff, where three energy charge differentiations were applied. An increased differentiation makes a change of production more attractive. The trend for production planning, where optimal electricity demand is reached, was found in Papers III and IV.

Paper V describes a way to combine two methods of analysis, i.e. to include results from Pinch Technology studies in the MIND optimization. By the MIND method, an optimization of the industrial utility and process subsystems can be performed. However, some analyses of energy saving possibilities are difficult to include in the MIND method. Pinch Technology, on the other hand, is developed for the analysis of heat recovery networks, where energy saving measures can be outlined. The combination of methods allows the whole industrial system, i.e. the subsystems of utility, process, and heat recovery network, to be included in a simultaneous multi-period optimization.

Paper VI describes the optimization of a refinery, where Pinch Technology studies are included in the MIND method. Results can be achieved in the combination of methods, that cannot be reached by the methods used separately. The simultaneous approach and the multi-period frame of the optimization allow flexibility in the interconnection between subsystems.
2. LITERATURE

Industrial analyses are accomplished in different ways depending on the aim and the means for the analysis. In literature, a large number of optimization and simulation methods can be found. This survey of literature embraces industrial energy systems optimization.

The minimum use of energy can be calculated from the analysis of a heat exchanger network using Pinch Technology. Pinch Technology is used to set targets for the minimum required external energy and to reduce the energy use by redesigning the heat exchanger network. A temperature enthalpy graph is drawn, where one of two composite curves represent all hot process streams and the other all cold process streams. The location of the closest distance between the two curves is called the pinch point. At this point, the minimum temperature difference for heat exchange between the process streams occurs. The optimal demand for hot and cold utilities can then be calculated, as well as the estimated heat exchanger area. Primarily, the minimum use of energy is calculated. The influence of investment and energy costs can be evaluated as a trade-off between minimum energy use and minimum system cost.

Heat exchanger networks can also be optimized with general optimization techniques.

An industrial energy system can also be represented as a system of known or available components, where design constraints and operational specifications are given. The structure and the operational conditions of the industrial system that satisfies a given goal, can be found by general optimization techniques. The formulation of the industrial problem can be performed in a way that facilitates the optimization effort. If, for example, all variables are continuous and all equations are linear, the optimization technique of LP (linear programming) is chosen. The standard method for solving LP problems is the simplex algorithm. When both continuous and discrete variables, e.g. binary integers, are used in the representation of linear equations a MILP (mixed-integer linear programming) program is required. Discrete or integer variables make the optimization problem significantly more difficult to solve. The algorithms used for solving integer problems are not as effective as the simplex method is for solving linear problems. Two algorithms, commonly used for the solving of integer problems, are the cutting-plane algorithm and the branch-and-bound algorithm. Both are combined with the LP technique. Another approach is the heuristic programming, where 'rules of thumb' and 'trial-and-error' procedures are employed to produce a feasible and near-optimal solution. This procedure is efficient for systems where general rules for the integer choices can be outlined, but gives poor results where the rules do not apply.
The addition of nonlinear functions to the problem requires a NLP (nonlinear programming) program. In nonlinear programming, several optimization algorithms are available. The choice of algorithm is important since one algorithm may be efficient for one type of problem but may fail for another. The efficiency or the rate of convergence may depend on the model formulation. The NLP problem can also be solved as a sequence of LP problems where the objective function and the constraints are linearized and some limiting value is moved at each iteration. Linearization can also be achieved by piece-wise linear approximations, where the correct sequence of pieces is achieved either in convex LP problems or by integer variables in MILP. When nonconvex functions are linearized, the use of LP does not always lead to a global optimum, whereas the use of integer variables eliminates this problem. Linear programming models have undoubtedly been successfully applied in convex nonlinear environment. The important question is then when a linearized equation does adequately represent the nonlinear reality. Some problems can be formulated with a special structure, for example, linear and quadratic terms included in the objective function and otherwise linear equations. They are solved by quadratic programming techniques. Efficient algorithms, known as SQP (sequential quadratic programming) methods, are also used as subroutines in general nonlinear programming programs where they provide a direction of improvement for the optimization. When continuous and discrete variables are used in the representation of nonlinear relations, the solution can be found by a combination of NLP algorithms and MINLP (mixed-integer nonlinear programming) techniques for integer search, approximation or decomposition of the problem. Grossmann (1990) has described and compared some methods for MINLP problems. The techniques for solving the optimization problems described above are shown by examples. The development of optimization techniques has provided many efficient algorithms and procedures. A more detailed description of optimization techniques and their application is, for example, given by Wagner (1969) and Williams (1985, 1993).

The above mentioned mathematical techniques for optimization can be used for the process system analysis, as well as the utility system analysis. A static representation of the energy system may be satisfactory in some cases, but in order to represent changes in the boundary conditions or in the process system, it may be necessary to include a time division in the optimization. The time division can be arranged in different ways depending on the degree of accuracy needed in the representation of the energy system. In some methods the time steps are fixed, while in other methods a flexible time scale is used. The flexibility allows a more detailed analysis.

A total industrial energy system embraces both the production processes and the utility part of the system. When thermal processes are represented or when possibilities
of heat recovery are assumed, the heat recovery network analysis is also required. The demand for energy is generated in the production processes, whereas energy is either directly supplied or converted to the desired kind in the utility part of the system. The industrial model should be flexible enough to represent single equipment units, parts of units or combination of units to enable the study of specific cases. The representation of equipment and flows must accordingly be performed in a general way. A generality of representation will also bring the opportunity to glide in accuracy so that part of the system can be represented in a high grade of accuracy while other parts can be left with a lower accuracy.

2.1. Heat exchanger networks - Pinch technology

The Pinch Technology method was developed by Linnhoff and Flowers in 1978. The method is used for the analysis of heat exchanger networks as is described by Linnhoff et al (1982). In literature, a large number of articles can be found where the application and the development of Pinch Technology is described. Only a few of them are mentioned here. For example, the application of Pinch Technology in the distillation of crude oil is studied by Sundén (1988) and the effect of heat pump installation at a refinery is studied by Farhanieh and Sundén (1990). The optimal integration of heat pumps in industrial processes and in CHP (Combined Heat and Power) plants is investigated by Wallin, Franck and Berntsson (1990) and Wallin et al (1992). Kotjabasakis and Gremouti (1992) have shown that the flexibility of the process system can be included in the method. The value of the process parameters can be changed (e.g. the level of temperature, pressure or flow) and a sensitivity analysis can be performed with the parameters changed within a specified range. This kind of analyses are made as successive calculations concluded as a three-way trade-off between cost, energy and flexibility by the aid of tables and diagrams. The utility system can be analyzed in a similar way as the process system as is shown by Hall, Parker and Linnhoff (1992) implying that Pinch Technology can be used for all parts of the industrial energy system. Other examples of method improvement concern aspects as environmental consequences, Smith (1992), and the scheduling of batch processes, Obeng and Ashton (1988).

Pinch Technology is widely used for industrial applications. The method gives a broad understanding of the heat exchanger network and the flows within it, although the global optimum is not guaranteed.
2.2. Heat exchanger networks - Mathematical methods

Heat exchanger network problems are also solved with mathematical methods. In the work of Cerda et al (1983) LP was used to find the minimum utility of the energy system. The heat exchanger network is represented as a transportation problem. The hot streams are then represented as sources of heat and the cold streams as sinks of heat at different fixed temperature levels, whereas the variables represent heat flows between the sources and the sinks. Large costs can be assigned for routes that are infeasible, which allows for the representation of forbidden stream matches. Several utility units can be represented at different temperature levels and costs. The pinch point is found by investigating the corner points and the ends of the linearized heating and cooling curves.

Papoulias (1982) describes the LP transshipment model. The advantage of this model is that it gives a problem which is smaller than the transportation model. In the transshipment model, the hot and the cold streams are still treated as sources and sinks, but the flow of heat between them is passing through intermediate nodes, where it is cascaded through temperature intervals. Forbidden stream matches are defined separately and can be handled in the model. In order to find the minimum number of heat exchanger units, the network is divided into two subnetworks, one above and one below the pinch point. The subnetworks are then formulated as MILP transshipment models, where the binary variables represent stream matches. The objective is to minimize the number of stream matches. The modelling technique of MILP is employed to synthesize, not only the heat exchanger network, but also the processing plant and the utility system of a chemical industry. This approach will give a heat integrated optimal plant structure, applied to a chemical industry with heating and cooling processes.

A sequential procedure is achieved when the minimum utility cost is predicted first and then the network structure where the least number of units is decided. Duran and Grossman (1986b) suggest a non-sequential procedure, where the heat integration is performed simultaneously with the optimization of the process flow sheet. In linear programming, a problem arises when the flow rates in the system are treated as variables and the temperatures of the flows only can be assigned discrete values. A set of constraints are introduced, where variable flow rates and temperatures can be handled. In this way, the location of the pinch points are allowed to vary according to the selection of process streams during the optimization procedure. The minimum utility cost target is considered simultaneously in the process optimization by the use of NLP.

In the work of Floudas, Ciric and Grossmann (1986) the sequential procedure of heat integration is further developed. The minimum utility cost and the location of the
pinch points are predicted, using the LP transshipment model described by Papoulias (1982). This allows the system to be divided into subnetworks at the temperature levels of the pinch points. The smallest number of matches can then be found for each subnetwork using a MILP transshipment model. A superstructure including the units predicted in the subnetworks is derived and the minimum investment cost for heat exchangers can be found by the use of NLP. The calculation is concluded by adding the configurations of each subnetwork. The flexibility of the energy system, where account is taken to the changes of flowrates and temperatures, will influence the performance of the heat exchanger network. Floudas and Grossmann (1986) have developed a multiperiod MILP transshipment program, which can handle the changes of pinch points and utility requirements. The time periods reflect known changes of flowrates and temperatures.

Colmenares and Seider (1989) combine the synthesis of an industrial utility system with the heat integration of a chemical process in a three-step procedure. First, the pinch point temperature of the process system is determined, either with Pinch Technology or with the method proposed by Papoulias and Grossmann (1983b). A cascade of temperature intervals are identified, which represent the exchange of heat between hot and cold streams. Above the pinch point, some of these intervals can be lumped together in a strategy suggested here, so as to reduce the size of the model. A NLP model is then used to minimize the annual cost and synthesize a utility system where electricity and heat flows are generated to meet the process demands. This system is represented as a sequence of Rankine cycles, combined in a cascade in accordance with the temperature intervals of the process system. Heat integration is then achieved between the condensers and the boilers and between the condensers and the processes. Finally, the configuration of the process heat exchanger network is identified.

As is explained by Grossmann (1992), the sequential decomposition of the synthesis problem involves some consequences, such as several solutions of stream matches and heat loads in one heat exchanger structure and the possibility to find local optima in the NLP model. Some modifications have been proposed to overcome these difficulties, but efforts have also been made to leave the sequential approach and to optimize the trade-off between energy, number of units and area simultaneously. Grossmann and coworkers have for this purpose developed the technique to solve nonlinear optimization problems including both discrete and continuous variables. A presentation of different optimization methods and their advantages and possibilities is given by Grossmann (1990).

The simultaneous approach represents another way of structuring the problem. Yee, Grossmann and Kravanja (1990a) have shown a NLP model for targeting the heat
exchanging area and the energy cost simultaneously. This model involves generation of
a superstructure, where the flows are separated and remixed in a number of temperature
stages. In each stage, heat can be exchanged between the hot and the cold streams. The
assumption of isothermal mixing between the stages simplifies the representation to a
set of linear constraints, whereas nonlinearities are represented in the objective
function. In this strategy, the concept of the pinch point is not used, implying that the
division into subnetworks and the rule of not placing heat exchangers across the pinch
point are eliminated. Yee and Grossmann (1990b) use the stage-wise superstructure to
model a MINLP problem, where the utility cost, heat exchanger areas and the selection
of matches are optimized simultaneously. This model allows the addition of constraints
for no stream splits, forbidden stream matches, required and restricted stream matches
and the use of multiple utilities. Yee, Grossmann and Kravanja (1990c) have also
embedded the heat exchanger network in the process structure, in order to
simultaneously optimize or synthesize the whole system. The constraints generated in
the targeting of energy and area for the heat exchanger network and for the optimization
of the trade-off between costs have been extended. The temperatures and the flow rates
of the streams were treated as variables and were included in the simultaneous
optimization of the process and its heat exchanger network. This extention involves
nonlinear terms, which may include uncertainty in finding the global optimum.

Another way to solve a heat exchanger network problem is to use the method of
simulated annealing as is described by Dolan, Cummings and Le Van (1989). The
simulated annealing algorithm is based on the Monte Carlo method, used in statistical
mechanical studies. It is an analogy between energy minimization in physical systems
and cost minimization in design applications. The system is described in the
optimization by a set of variables calculated in order to globally minimize an objective
function. In physical systems, for example a crystal, a disordered structure must first
be annealed by melting and then by cooling very slowly in order to reach the minimum
energy crystalline state. In a design application, an analogy for the annealing
temperature with the unit cost is used. This temperature controls the probability for
accepting increases of cost, caused by random changes of the variables in the system.
This technique reduces the problem of getting trapped in local optima. During the
simulation procedure the 'annealing temperature' is reduced periodically from an
initially high value until no changes of the variables are accepted. The final choice of
variables will then represent the minimum cost of the system. An optimal or near-
optimal solution, independent of the initial guess, can be reached but, however, the
global optimum is not guaranteed in a finite amount of calculation time.

The mathematical methods give a thorough analysis of the heat exchanger
network. The choice of methodology for the analysis is significant, as was shown in
the references mentioned above. Analysing the process system together with the heat exchanger network renders new insights, even though it involves the solving of difficult nonlinear problems. Large efforts are made within the chemical industry for finding the optimal structure of thermal process systems. The approach to include the aspect of time and the representation of flexibility, of the utility and the process systems, is of great importance.

2.3. Industrial optimization - Mathematical methods

In optimizing an industrial energy system, the method of linear programming can be used although nonlinearities are present. When nonlinear relations occur, they can be treated by an iterative procedure of LP calculations, where linear approximations are successively altered to achieve a better fitness to the nonlinear relation. These functions can also be linearized. The inclusion of nonlinearities in the industrial model will increase the computational effort whether linearizations are used or not, but they can be handled. Since nonlinearities frequently occur in industrial systems, it is necessary either to represent them in a nonlinear model or to include linearized expressions, which can be represented in LP or MILP.

The scheduling of the thermal generating units of an industry can be accomplished by the use of MINLP, as is shown by Turgeon (1978). The costs for start-up, stand-by and operation are minimized, while other restrictions such as minimum stop and operation periods and the frequency of starts per day, are simultaneously considered. The energy production is represented as a constant value throughout each time step and the number of time steps are chosen to meet the known curve of energy demand, i.e. the production is set equal to the demand.

At Brookhaven National Laboratory (BNL), models for large scale industrial process optimization of specific industrial branches were developed by Pilati and Sparrow (1980). The models are used for energy demand predictions, process technology choices and policy analyses regarding energy taxes and investment tax credits. The optimization is based on LP and MILP, where binary integer variables are associated with economies of scale. The minimum after-tax costs are calculated in a time period of 25 years, where a typical year is modelled for each five-year-period. Each model addresses an entire industrial branch and is not intended for use at any particular plant, although the models can be modified for this purpose. At BNL, other models for the evaluation of national energy supply/demand distribution systems are also developed. Kydes (1990) describes the BESOM model (Brookhaven Energy System Optimization Model) which is a single-period LP model and the TESOM model...
(Time-stepped Energy System Optimization Model), which is also presented by Kydes and Rabinowitz (1981). The TESOM model is used for regional strategic planning, where energy conservation options can be studied in economical terms. The model is solved as a sequence of LP programs, one for each time step. The transition of information between time periods is facilitated by control equations.

Nishio et al (1983, 1985) use LP and MILP in a single-period model to minimize the fuel consumption in chemical process industries. The optimization procedure is performed on two levels, an upper level for coordination of the total system and a lower level of subsystems where technology candidates are chosen. The subsystems represent the heat and power supply system, the process system and the cooling system. Integer variables represent the changes in heating, power and cooling demands which occur when energy conservation technologies are employed. On the upper level, a trial-and-error calculation is used. This method aims at structural optimization in the choice of energy conservation technologies at constant material balances.

In synthesis problems, where several alternatives of process units are available and both discrete and continuous decisions are involved, a mixed-integer nonlinear problem may arise. Grossmann and Santibanez (1980) use linearizations to synthesize chemical processes and steam generating systems in mixed-integer linear programming. The chemical process system is here represented by the material flows of the processes. The investment costs and their expansion are expressed in linear terms by binary integer variables as a function of equipment capacity. The objective is to find the maximum net present value of investments in the structure of the process system. The flexibility of the process system, with respect to variations in prices and demands, is represented in the model by multiple time periods. The multiperiod optimization method is also used for the synthesis of steam generating systems, where the minimum annual cost is sought. Linearizations are performed for fixed and variable terms of the cost function and for the relation between the mass flows of steam in an extraction steam turbine. The electricity output from the turbine is given as an input requirement.

Papoulias and Grossmann (1983a) describe the modelling of an industrial utility plant by MILP. The optimal structure and the operating conditions are found by minimizing the total annual cost in a single-period model. The demand for electricity and steam is considered constant during the optimization period. Parameters, like temperature and pressure, are stated at fixed values. Operating conditions can then be analyzed through a set of discrete values, each representing a specific parameter choice, allowing linearity to be maintained in the performance equations. A similar approach is used by Papoulias and Grossmann (1983d), where an industrial utility plant is
synthesized in order to satisfy time-varying demands of electricity and steam. A multi-
period MILP model allows the flexibility of the demands to be represented.

Papoulias (1982) and Papoulias and Grossmann (1983b) investigate the
possibilities of process energy saving measures in a heat recovery network. For this
purpose the LP transshipment model is used in combination with MILP in a procedure
described in the previous chapter.

Papoulias and Grossmann (1983c) also use MILP to represent the total process
system. The industrial system is here regarded as a combination of three components,
the chemical plant, the heat recovery network and the utility plant. These components
are combined and synthesized simultaneously in one single-period model, as well as in
a step procedure. The simultaneous approach renders a better optimal value than does
the decomposition into a step procedure. The reason for this is the possibility in the step
procedure to create process system utility demands, which cannot be provided
efficiently by the utility system. It is evidently of great importance to represent the
process system including the heat recovery network and the utility system in a manner
that allows interchange between the systems. It also seems to be interesting to include
the aspect of time in this concept for the representation of the flexibility of the total
system.

The synthesis of process systems by simultaneous structural and parameter
optimization using MINLP is addressed by Duran and Grossmann (1986a). An
algorithm is proposed for solving the MINLP problem. It is here possible to avoid the
discretization of nonlinear continuous variables, which is the approach of Papoulias and
Grossmann, and also to reduce the number of binary variables. Since it is difficult to
determine the convexity of the involved nonlinear functions, especially in large process
systems, the global optimum can not always be guaranteed in this procedure. Duran
and Grossmann (1986b) describe a way to simultaneously heat integrate and optimize
chemical processes by NLP. The requirement for the performance of a simultaneous
analysis is the formulation of the heat integration problem so as to allow variable flow
rates and temperatures of the process streams. A set of heat integration constraints are
introduced, which do not require defined temperature intervals. These constraints are
based on the pinch points, located according to the stream conditions selected in the
process optimization. Multiple utilities can be handled, whereas the investment costs of
the actual heat exchanger units can not be included since that would involve discrete
decisions.

Ducrocq and Bauchet (1984) use LP to analyze industrial sectors in order to
examine the possibilities to introduce new electrical technologies. A typical industry is
studied on the basis of statistical data. Both material and energy flows are considered in
the representation of production processes and utilities. The minimum annual cost for
energy and investments is the criterion for the optimal operation and the selection of units. The year is divided into electricity price periods and constant demand periods. Nonlinearities in the investment cost function are linearized by piece-wise linear approximations. Ducrocq (1985) also uses MILP to analyze industrial cogeneration systems, where the objective is to minimize the system cost. Nonlinear load curves of boilers and turbines are linearized by piece-wise approximations and binary variables. There are four operating modes of the steam turbine to choose from and three for the boilers. The model can be extended to multiperiod operation, where the year can be divided into a number of time periods.

Some models are especially developed for the analysis of industrial energy supply systems. The process energy demand is then given as input to the analysis. The OPERA model (l'OPtimisation de l'Energie en RAffinerie) is developed by Bloch (1987) for the cost optimization of steam and electricity production in refineries. Both energy and material balances are included. In order to reduce the optimization effort, the enthalpies of the flows are assumed constant in each equipment node. This assumption eliminates a nonlinear formulation from the mass balance and leaves nonlinearities only in some of the operation characteristics. These can be linearized and the optimization is performed by the use of LP in convex cases and MILP in nonconvex cases. The analysis is performed in steps by successive optimizations, where the enthalpy values are corrected in each step, until convergence is reached. Another model, which is used for the simulation and cost optimization of an industrial energy supply system is SECI-MANAGER, developed by Coeytaux (1984). The system is formed by 'building blocks' taken from a library of standard equipment with preprogrammed equations. The optimization algorithm is developed for solving nonlinear equations and for handling discrete variables. The model aims at including the whole industry, for on-line use, to continuously and automatically optimize the plant operation.

Sundberg (1989) developed the MIMES model, which is a LP single-period approach to optimize industrial or municipal energy systems, including energy supply and energy demand. Processes can be represented by six choices of flow relations between the input and output material and energy flows. Nonlinearities were initially handled by successive LP optimizations to reach the minimum value of the objective function. The model was since further developed for strategic planning of municipal waste management systems. Possibilities to handle nonlinear relations in NLP and MILP were also included, Sundberg (1993).

Mathematical programming techniques are widely used in the area of industrial optimization. They facilitate the handling of large amounts of data and allow for advanced mathematical calculations. The approach of the analysis may vary widely.
Some methods are focusing on specific parts of the total industrial system, while others embrace the whole system by simultaneous or sequential approaches.

2.4. Concluding remarks

When industrial energy systems are analyzed, the representation of the system can be performed with desired accuracy. One approach to industrial optimization, used in some of the references, is to divide the industrial system into subsystems, treated separately in the analysis. Such subsystems are: the utility system, the process system and the heat recovery network. It is then possible to concentrate on one subsystem and let the other parts of the industry be represented merely by constant parameters. However, some disadvantages can be found in this procedure. If, for example, the utility system is analyzed and the energy demand of the process system is represented at fixed values, the flexibility is not included and the interaction between the subsystems is lost. If the process system is analyzed in order to find energy recovery possibilities, and the utility system is not included, suboptimal solutions can be found, where the energy savings achieved in the process system lead to a reduced efficiency in the existing utility system, that more or less eliminate the savings. It seems important to include the whole industrial energy system in the optimization in order to represent the flexibility and the optimal interconnection between the subsystems. Efforts have been made to combine optimization of industrial subsystems in sequential, as well as simultaneous, procedures.

When processes involving thermodynamical changes are studied, nonlinear relations will appear in energy and material processes. Nonlinear relations are also found in cost optimization, where investment cost is expressed as a function of equipment capacity. These nonlinearities can be handled in various ways, depending on the representation chosen for the system, as is shown in the references. Even if thermodynamical nonlinearities can be treated, some approximations are necessary. The optimization of heat recovery systems is often based on single-period steady-state conditions where, for example, heat capacities and heat transfer coefficients can be assumed constant. In utility and process systems, there may be a distinction between optimizing the equipment structure or the operating conditions, even if the system may be formulated to obtain both. In the synthesis of equipment units, chosen from a library or a superstructure, the choice and the size of units are the essential issues. The selected structure must be feasible for the whole cycle and not only for single periods. In finding the optimal operating conditions of an existing or a fixed structure of units, the whole range of flow capacities are required.
The flexibility of the subsystems can be seen as an option to be utilized in the optimization. In order to include flexibility, a time division of the considered optimization period is introduced. Since flexibility not necessarily refers to the same aspects in the subsystems, different time scales may have to be used or a total flexibility in the choice of length and number of time steps. In the mathematical optimization methods described here, the representation of the industrial system can be formulated to allow flows to pass between time steps, but all time steps are simultaneously optimized. The flexibility of an industrial process system might concern changes in the production level, product mix, availability and price of raw materials, storage capacity, personnel working hours, climatic changes etc., while the utility system is influenced by availability and price changes of fuel and electricity as well as energy demand changes of the process system. When the utility and the process systems are combined, and the flexibility of the systems is included by the application of an integrated time division, the optimal operating conditions of the two systems in co-operation can be seen. The heat recovery network, which may influence both the utility and the process system, is often represented in single-period steady-state models, where thermodynamical properties can be represented. These assumptions, which may be necessary in the heat recovery network analysis, render the combination of subsystems more difficult in the flexibility ranges, applied in the utility and process systems.

Large process systems involving many different units would require much information, like performance data and design parameters, for an accurate description in the optimization. Since a process system may include a large variety of processes and equipment units, a method to reduce the amount of input data is convenient. A general way to describe processes, where material and energy flows are included, can be achieved by a library of units with various definitions. By this concept equipment units can be divided or aggregated, which enables highlighting parts of the industrial energy system if a higher level of accuracy is needed.

An industrial optimization method, with ability to meet these issues, should include the following aspects:

- a flexible time division,
- the choice of different levels of accuracy in parts of the energy system,
- the representation of energy and material flows in the process system,
- the representation of nonlinear relationships,
- a simultaneous representation of the whole industrial system.
A flexible time division admits the representation of events and changes, occurring in different parts of the system during the optimization period. When the industrial subsystems can be included simultaneously, the interconnection between them can be achieved at the limits represented in each time step. In this way, a change of the production level (material flow), that involves an altered energy demand, may affect the operation of the industrial utility system. Similarly, a change of the process structure, where the choice of process technology, capacity of units, or investment considerations are concerned, may also affect other parts of the system as well as the system cost. The ability to represent with high accuracy those parts of the system which influence the system cost then becomes important. Other parts, where the influence on cost is low, should preferably be represented by a lower accuracy in the node network. This procedure will reduce the amount of input data and also the size of the node network. It is evident that nonlinear relations in energy demand, investment cost and energy conversion efficiency, will affect the total cost of the system, when flexibility is considered in the optimization.

In industrial optimization, where the diversity between branches and the flexibility of boundary and process conditions are considered, the fundamental conditions mentioned above must be included. The analysis methods, referred to in the survey of literature, have been developed with the purpose of other goals and do not include all aspects.
3. THE OPTIMIZATION METHOD

The MIND method is a way to generate a model of an industry, where each case is individually treated and specific conditions can be included. The generation of the model is performed by the MIND Fortran code. Input data and specifications for the model formulation are given in a separate file and in the main code. The model is optimized by the ZOOM program for mixed-integer linear programming. In the following, different aspects of the modelling procedure are described.

3.1 System cost and objective function

The optimization is performed with the objective to find the minimum system cost. This goal includes costs and incomes considered significant for the industrial energy system. The mix of costs may vary in different studies, but costs for energy, raw material and investment are normally included. Occasionally, it is possible to add an income from selling energy. In most industrial cases, the time horizon for the optimization is short enough to involve known costs. But, if needed, assumptions for a cost prognosis can be introduced.

Time division is made in accordance with known cost changes and the flexibility of the production processes, which enable including the variation of boundary conditions, as well as internal system changes. Two time scales are used, one for short term and one for long term changes. When an industrial energy system is studied over a five year period, the short term time scale may divide one year into a desired number of time steps, while the long term time scale represents five multiples of the short term time division. The length of the short term time steps can be adjusted for each long time step. It is then possible to choose the number of short time steps, each with optional length, as well as the number of long time steps. Special situations which occur during the studied period can be included in the optimization. Such situations could be planned productions stops, changes in availability of raw materials or fuel, and changes in storage capacity of energy and material.

The energy costs are given as input values for each time step of the calculation. The electricity subscription embraces the subscription, demand and energy charge. The charge for the subscribed power level can be included, but assuming the power level is not exceeded during the calculation time, the charge is usually not represented. The demand charge is applied for the peak hour demand during winter daytime. Depending on the time division chosen, the demand charge can be applied in three different ways:
- For one time step, selected from all available short steps, where the highest average energy flow per hour occurs.

- For a specified set of short term steps, where the highest average energy flow per hour is chosen.

- For all short term time steps.

These three possibilities to introduce a cost, connected to the purchase of electricity, at different time periods, can be utilized for the demand charge or for the subscription charge plus the demand charge. Fuel costs are expressed in terms of energy, volume or mass units. When new kinds of fuel are introduced, a realistic assumption of the cost can be made. The cost for raw materials may be included in the optimization, since this cost sometimes affects the optimal result.

Investment and maintenance costs, referring to equipment units of known size, are included in the optimization by the existence or nonexistence of units, represented by the value of a binary integer variable. The costs related to one unit or an aggregated group of units are represented in a sum, valid for the calculation period. The depreciation of investment costs can be calculated either in the way used at the specific industry or by other methods. An equipment unit, already paid for, may be represented without investment cost but, on the other hand, maintenance costs might have to be introduced. In a structural optimization, where the configuration of units is analyzed, the capacity of each unit is significant for the total system. The investment cost is

![Investment cost function alternatives](image.png)

Fig. 1. Investment cost function alternatives.
influenced by the reduction or expansion of equipment capacity. Such a change is represented either as a stepwise function or a linearized continuous function, see Fig. 1. The stepwise increasing investment cost is represented in the objective function in the following way, where step 1 and step 2 are given as input data for the node (n) concerned:

\[ c_{in1} \cdot IN_n + c_{in2} \cdot IN2_n \]

(\(c_{in1} = \text{step 1}, c_{in2} = \text{step 2 - step 1}\))

The continuously increasing investment cost is represented in the objective function and in the subsequent additional equations. The step and the slope of the cost function are required as input data:

\[ 1 \cdot c_{in} \]

\[ c_{in} - \text{step} \cdot IN_n - \text{slope} \cdot MC_n \geq 0 \]

\[ MC_n - PM_{ijn} \geq 0, \quad i = [I, I], j = [I, J] \]

A similar procedure is used, when the capacity of the equipment unit is expressed in terms of steam or electricity flow.

The formulation of the objective function depends on the structure of the node network and the costs involved in the industrial system. One example is given in Paper I, where a pulp and paper mill is described. Another formulation, presented below, is achieved in Paper VI, where the system cost of a refinery is optimized. All entering material (M), fuel (F), and electricity (E) flows are multiplied with the cost occurring in each time step. The possibility to sell heat (S), at the price valid in each time step, is represented as a negative term in the objective function. The electricity peak load (P) is included in the objective function for \(p\) number of short time steps \((j = [1, p])\) and each long time step \((i = [1, I])\). Eq. 5 represents the general formulation for this optimization problem. In this case, the peak load charge is applied for the first long time step and subsequently included at zero cost. Since existing equipment units are considered, the binary integer variables (IN) are represented with zero investment costs.

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \left[ \left( \sum_{km=1}^{KM} M_{ij,km} \cdot c_{ij,km}^M \right) + \left( \sum_{kf=1}^{KF} F_{ij,kf} \cdot c_{ij,kf}^F \right) + \left( \sum_{ke=1}^{KE} E_{ij,ke} \cdot c_{ij,ke}^E \right) \right] -
\left( \sum_{ksi=1}^{KSI} S_{ij,ksi} \cdot c_{ij,ksi}^S \right) + \sum_{i=1}^{I} \sum_{j=1}^{p} \sum_{ke=1}^{KE} (P_{ij,ke} \cdot c_{ij,ke}^P) + \sum_{kin=1}^{KIN} (IN_n \cdot c_{in})
\]
3.2 Process and utility representation

The industrial production system is composed of nodes and branches, representing process units and flows of energy and material, expressed on an hourly basis. Energy flows represent steam, electricity, hot water etc., whereas fuel is represented either as a material or an energy flow. The industrial production is represented by a material flow, which is distributed to the production processes through the input node, passing through process nodes, generating an energy demand and finally, aggregated in the output node. The whole node system is generated once for each time step, whereas the aggregation node for material flows can be specified in three different ways:

1. One aggregation node for each short term time step.
2. One aggregation node for each long term time step.
3. One aggregation node for the whole calculation.

The choice of representation for the material flow aggregation node depends on the flexibility of the production processes. When the production is kept on a stable level and no shift between the time steps is desired, the production level is specified for each time step in the first choice of representation. If, on the other hand, the production can be shifted between the short time steps, the average material flow for each long step is specified by the second representation. The optimal production level is then found for each short step. An upper and an optional lower limit of the material flow is given in each process node, which represents the capacity of the equipment units or the flexibility of material flows. When the third representation is chosen, the material flow is aggregated in one node for the whole optimization period. In this approach, the average production demand is given for the whole period and the optimal material flow level is calculated for each step. To accomplish this kind of representation, the production level needs to be expressed and compared for different periods. The flow level is treated on an hourly basis and a time factor is introduced in the equation for aggregation of material flows. The material balance over the aggregation node in the second representation is:

$$\sum_{j=l}^{J} \sum_{k=L}^{K} M_{ijk} \times \left( \frac{h_j}{\sum_{j=1}^{J} h_j} \right) \geq \text{(Average hourly production demand)}_i, \quad i = [I, I] \quad (6)$$
In this case, the equation is repeated for each long term time step with new input values for the average production demand. The index k refers to input material flows to an aggregation node.

The material flow represented in a production process may undergo physical and chemical changes. The best comprehensibility of a node network is achieved when such changes are represented as close to reality as possible. In the MIND method, the material flow of a process node can be altered by a multiplying factor. Flows can also be aggregated and distributed in a percentage relation of the total flow through a node.

![diagram](image)

Fig 2. Seven possibilities to express energy demand as a function of the material flow.
The flexibility of the production level is defined by bounds for the material flow. An upper bound may represent the maximum unit capacity, while upper and lower bounds may represent the limits for the flexibility of material flows. Bounds are given either as new input values for each time step or as a constant value for the whole calculation.

The energy demand of process nodes is represented as a function of the material flow. All process nodes are specified by the choice of energy demand functions. The electricity demand function is chosen from seven alternatives, see Fig. 2. The steam demand is chosen from three kinds of function alternatives which are shown in Fig. 2 as the cases a, b, and c. The performance of the processes is specified by input data for each node. With reference to Fig. 2 the following data is required:

Case a  slope (ΔE/ΔM),
Case b  step 1, step 2 and end of first step (ST1),
Case c  step and slope,
Case d  slope 1, slope 2 and breakpoint (BP),
Case e  step, slope 1, slope 2 and BP,
Case f  slope 1, slope 2 and BP,
Case g  step, slope 1, slope 2 and BP.

The different cases are represented by the equations 7 - 31, applied for the intervals i = [1, I], j = [1, J], k = [1, K] and n = [1, N]. The chosen energy demand function involves the sum of input energy and material flows to the process node represented.

**Case a**

\[ \Sigma E_{ijk,in} - \text{slope}_{ijn} \times \Sigma M_{ijk,in} \geq 0 \]  
(7)

This linear energy demand function is applied, with reference to Fig. 3, as is shown in the example below:

\[ (E_{117} + E_{118} + E_{119}) - \text{slope}_{11n} \times (M_{111} + M_{112} + M_{113}) \geq 0 \]  
(8)
Case b

\[ \sum E_{ijk, in} - \text{step 1}_{ijn} \times IB_{1ijn} - \text{step 2}_{ijn} \times IB_{2ijn} \geq 0 \]  
(9)

\[ B_{1ijn} + B_{2ijn} - \sum M_{ijk, in} \geq 0 \]  
(10)

\[ \text{Constant} \times IB_{1ijn} - B_{1ijn} \geq 0 \]  
(11)

\[ \text{Constant} \times IB_{2ijn} - B_{2ijn} \geq 0 \]  
(12)

\[ IB_{1ijn} - IB_{2ijn} \geq 0 \]  
(13)

\[ B_{1ijn} \leq ST_{1ijn} \]  
(14)

Case c

\[ \sum E_{ijk, in} - \text{step}_{ijn} \times IN_{n} - \text{slope}_{ijn} \times \sum M_{ijk, in} \geq 0 \]  
(15)
**Case d**

\[ \sum E_{ijk,in} - \text{slope } 1_{ijn} \times B_{1ijn} - \text{slope } 2_{ijn} \times B_{2ijn} \geq 0 \] (16)

\[ B_{1ijn} + B_{2ijn} - \sum M_{ijk,in} \geq 0 \] (17)

\[ B_{1ijn} - B_{Pijn} \times IN_n + (1 - IB_{2ijn}) \times \text{constant} \geq 0 \] (18)

Constant \* IB_{2ijn} - B_{2ijn} \geq 0

\[ B_{1ijn} \leq B_{Pijn} \] (20)

**Case e**

\[ \sum E_{ijk,in} - \text{step } 1_{ijn} \times IN_n - \text{slope } 1_{ijn} \times B_{1ijn} - \text{slope } 2_{ijn} \times B_{2ijn} \geq 0 \] (21)

\[ \sum M_{ijk,in} - B_{1ijn} - B_{2ijn} \geq 0 \] (22)

\[ B_{1ijn} - B_{Pijn} \times IN_n + (1 - IB_{2ijn}) \times \text{constant} \geq 0 \] (23)

Constant \* IB_{2ijn} - B_{2ijn} \geq 0

\[ B_{1ijn} \leq B_{Pijn} \] (25)

**Case f**

\[ \sum E_{ijk,in} - \text{slope } 1_{ijn} \times B_{1ijn} - \text{slope } 2_{ijn} \times B_{2ijn} \geq 0 \] (26)

\[ B_{1ijn} + B_{2ijn} - \sum M_{ijk,in} \geq 0 \] (27)

\[ B_{1ijn} \leq B_{Pijn} \] (28)

**Case g**

\[ \sum E_{ijk,in} - \text{step } 1_{ijn} \times IN_n - \text{slope } 1_{ijn} \times B_{1ijn} - \text{slope } 2_{ijn} \times B_{2ijn} \geq 0 \] (29)
The recovery of heat can be represented in two different ways in the MIND method. It can either be included as a reduction of the process energy demand, i.e. the recovered heat is consumed within the process, or it can be defined as a function of the material flow, which will result in a usable flow of, for example, hot water or steam. Examples of the two distinctions of heat recovery are given in the optimization of a refinery, see Paper VI. A heat recovery network is suggested for the reduction of energy demand in the distillation units, whereas the heat recovery from cooling the refinery products results in a heat flow which can be utilized in other parts of the system or, in this case, sold to the municipal district heating system. The representation of recovered heat as a function of the material flow is accomplished similarly as the energy demand functions, see cases a and c in Fig. 2.

The process related energy demand is included in the representation of the process nodes, where the flexibility is accomplished by a change of the material flow level. Industrial systems sometimes have energy demands not related to the production processes, i.e. heating of premises, cold storage and services to external facilities. These demands can also be included in the MIND representation, usually defined by constant input data given for each time step. In Paper I, where a pulp and paper mill is studied, the external demand of electricity and steam is included in this way. Another approach is to represent the possibility to export energy and finding the optimal flow level, where flow limits can be used if required. This may or may not include an income to the industrial system. In the Papers II and VI, this kind of representation is used for delivery of heat to the municipal district heating system, which renders an income to the industry, and the possibility of cooling by sea water, representing an unlimited way to dispose of heat.

The representation of batch processes can also be accomplished in the MIND method. Batch processes could concern a line of consecutive process equipment or several units, that operate simultaneously or in various sequences. When a process route, where several products can be processed, is represented, alternatives for energy demand and investment costs are given as parallel node options, while production changes are represented by the time division. When several units are operating simultaneously or in specific sequences, these requirements must be indicated in the model. One way of representation is parallel node options, where the nodes indicate
possible combinations of units. Another approach is to utilize binary integer variables in logical constraints to represent unit combinations.

The industrial utility system is represented by energy distribution and conversion nodes. These nodes are generally represented with high accuracy, i.e. one or several nodes per utility equipment.

The representation of external electricity is accomplished by a distribution node passing electricity to the processes and to other utility nodes where electricity demand exists. A node for electricity distribution represents one specific tariff. If several electricity utilities are available at different tariffs, they are represented by the required number of input electricity nodes. The energy balance of such nodes is shown in Eq. 32. The equation indexes refer to the input and output flows of the distribution node:

\[ E_{ijk,\text{in}} - \sum E_{ijk,\text{out}} \geq 0, \quad i = [1, \ I], j = [1, \ J], k = [1, \ K] \] (32)

The electricity peak demand is equal to the highest energy flow, calculated as the average per hour, of a specified time period, which can be defined in three different ways. As is mentioned earlier, one possibility is to select one time step from all available time steps, where the highest average energy flow occurs:

\[ P_{ilk,\text{in}} - E_{ijk,\text{in}} \geq 0, \quad i = [1, \ I], j = [1, \ J], k = [1, \ K] \] (33)

Another approach is to select a set of short term time steps, from which the highest average energy flow is chosen:

\[ P_{ilk,\text{in}} - E_{ijk,\text{in}} \geq 0, \quad i = [1, \ I], j = [1, \ p], k = [1, \ K] \] (34)

The electricity peak demand can also be calculated for all short term time steps:

\[ P_{ijk,\text{in}} - E_{ijk,\text{in}} \geq 0, \quad i = [1, \ I], j = [1, \ J], k = [1, \ K] \] (35)

In some industrial systems, external steam or heat can be purchased. Such facilities are also represented by a distribution node. A coefficient for the distribution efficiency, effcoe, may be introduced, as is shown in Eq. 36. This coefficient could reflect the difference between the purchased amount of energy and the amount delivered at the place of use in the process system. In the following equations, the intervals \( i = [1, \ I], j = [1, \ J], k = [1, \ K] \) and \( n = [1, \ N] \) are valid. The variable, PS, is restricted with an upper bound and at option a lower bound, that represent the limits of capacity.
Energy conversion nodes represent the conversion of fuel into steam, electricity into steam, fuel into electricity, or steam into electricity. The conversion of fuel into steam can be represented with a constant conversion efficiency throughout the whole capacity range of the unit, Eq. 38. In cases where the optimal flow level differs widely between the time steps, separate constant efficiency values can be given for each step in order to represent the relation between efficiency and output capacity. However, this procedure requires a reoptimization:

\[ F_{ijk,\text{in}} \cdot \text{effcoeij}_n - \sum S_{ijk,\text{out}} \geq 0 \]  

(38)

The conversion efficiency can also be expressed by a nonlinear relation (see Fig. 2, case d) between input fuel and output steam, shown in the equations below. A fuel conversion factor, \( \text{fuelcon} \), allows for the representation of fuel, either as a material or an energy flow. The output capacity of steam is restricted by an upper limit represented by a bound on the PF variable, Eq. 44. When needed, a lower limit can also be used.

\[ F_{ijk,\text{in}} \cdot \text{fuelcon}_{ij_n} \cdot \text{slope} 1_{ij_n} \cdot S_{Aijn} - \text{slope} 2_{ij_n} \cdot S_{Sijn} \geq 0 \]  

(39)

\[ S_{Aijn} + S_{Sijn} - S_{ijn} \geq 0 \]  

(40)

\[ S_{ijn} - \sum S_{ijk,\text{out}} \geq 0 \]  

(41)

\[ S_{Aijn} - B_{Pijn} \cdot I_{Nn} + (1 - I_{Fijn}) \cdot \text{constant} \geq 0 \]  

(42)

\[ \text{Constant} \cdot I_{Fijn} - S_{Sijn} \geq 0 \]  

(43)

\[ P_{Fijn} - S_{ijn} \geq 0 \]  

(44)

The demand for electricity in a fuel conversion node is expressed by the kind of function shown in Fig. 2, case c:

\[ \sum E_{ijk,\text{in}} \cdot \text{stepi}_{ijn} \cdot I_{Nn} - \text{slope} \cdot F_{ijk,\text{in}} \geq 0 \]  

(45)
A cost, related to the existence of an input fuel flow to a conversion node, can be introduced in the objective function by a binary integer variable, $FW$. One example is shown in Paper I, where a fuel of mixed bark needs a constant combustion support of fuel oil. The cost for support fuel oil should be included only when mixed bark is consumed. This condition is represented by the following equation:

$$\text{Constant} \times FW_{ij}n - F_{ijk,in} \geq 0$$

(46)

The conversion of fuel into electricity is represented by a conversion node, where the relation between fuel and electricity flows is shown in Fig. 2 case c. This kind of energy conversion could, for example, describe the characteristics of a gas turbine:

$$E_{ijn} - \sum E_{ijk,out} \geq 0$$

(47)

$$F_{ijk,in} \times \text{fuelcon}_{ijn} - \text{step}_{ijn} \times \text{IFA}_{ijn} - \text{slope}_{ijn} \times E_{ijn} \geq 0$$

(48)

$$\text{Constant} \times \text{IFA}_{ijn} - F_{ijk,in} \times \text{fuelcon}_{ijn} \geq 0$$

(49)

$$PE_{ijn} - E_{ijn} \geq 0$$

(50)

$$PE_{ijn} - E_{ijn} \leq 0$$

(51)

The conversion of steam into electricity, where various operating conditions of a steam turbine can be chosen, is described in Paper II.

### 3.3 Calculation procedure

In modelling an industrial energy system, the node network is designed to include conditions that might influence the system cost. Input data are separated into flow data and node data. Node data are treated in the calculation program EXCEL to the form needed in the MIND model. The flow input data are given in a separate file, read from the MIND code in order to generate the input file to the ZOOM program. The generation of the variables and equations included in the optimization matrix is directed by the information given in the flow input data file.

The industrial model, generated with the MIND method, is optimized with the ZOOM computer code for zero/one mixed-integer linear problems. The optimization techniques used are the simplex method with bounded variables and the branch-and-
bound method. These are standard techniques for a convenient way to find the global optimum of the problem. The computer calculation time increases rapidly with the number of binary integers used in the representation of the industrial energy system. Therefore, it is important to keep the number of binary integers at a reasonable level.

The optimization result is achieved as a list of variables and their optimal values. An analysis of output data is required. This is conveniently performed by scheduling output data in a sequence corresponding to the node network, where flow values easily can be compared and checked.

Restrictions can be introduced in the optimization in order to evaluate specific flow situations or node structures. For this purpose, variation of bounds and selection of binary integers are utilized.

3.3.1 Check of calculation

In the MIND method, the binary integers connected with the choice of nodes in the network, are given a separate equation, where the integers can easily be assigned the value of zero or one. The correctness of each optimization result is checked with several calculations, where other node structures are imposed. The optimal node structure can be validated in this way. This procedure also provides valuable information about the flexibility of the system cost for various node structures. The optimal flow distribution is checked by simple hand calculations.
4. COMMENTS ON THE ENCLOSED PAPERS

The papers included in this thesis are all based on the MIND method. The intention of
the optimization is slightly different in each case. The purpose is to present the
possibilities of the MIND method.

4.1. Choice of accuracy level in the node representation

The MIND method represents a general way of generating a node network model for
any specific industrial case. Input data and a key code is given for the generation of the
node structure, which represents the industrial system. The node structure is easily
generated with respect to the number of nodes and branches, as well as the time
division of the system. In the key code, the desired equations are chosen for each node
in the structure. In different industrial branches, a wide variety of process performances
can be found. An exact simulation of various kinds of equipment would require specific
input data for each kind and a tedious work to generate an industrial model. In the
MIND method, the representation of process equipment units is performed in a general
manner, where all kinds of equipments can be included. Since every node represents
different processes in a general way, the method allows for the representation of
processes at various levels. One node may represent a process equipment, a part of a
process equipment or several aggregated equipment units.

The MIND method can be used for a structural analysis where several node
options are available in one flow path or an optimization of the flow level in a fixed
structure. In both cases, the least costing alternative is found in the optimization. It may
also be convenient to combine these possibilities in one model. A higher level of
accuracy can then be used where node options are introduced or where the operation
conditions need a thorough representation. Other parts of the industrial system can be
represented at a lower level of accuracy, i.e. with fewer nodes.

In paper I, the production system of a pulp and paper mill is represented with
reduced accuracy. Three major parts of the production system are represented as nodes,
the barking plant, the sulphate pulp mill and the paper mill. This distinction of nodes is
chosen from the availability of input data for the electricity and steam demand, as well
as from the production flow. The measuring unit for the production flow is changing as
the incoming wood is processed to chipped wood, pulp and paper. The changes occur
at the passage between the nodes and can be represented by a multiplying factor. The
addition of recycled fibres is defined by a percentual aggregation of two incoming
flows to a node. In this kind of representation, a wide range of production flow changes can be accomplished. The choices are given in the key code at the generation of the industrial model. The seasonal changes in energy demand are not equal in the different parts of the process system. These changes are also reflected in the chosen node representation.

The production flow of the refinery given in paper II has another structure. In this case, it is not as easy to find natural dividing parts in the production system, and accordingly the production system of the refinery is represented as one single node. Another reason for this choice is the suggested addition of a heat recovery network, with and without a heat pump, to the production system (paper VI). These two additional choices can then be represented as two parallel flow options to the original production process node. Binary integers are used for the selection of nodes in the system. In the node representation of paper VI, the different options of production nodes can easily be chosen in order to evaluate the optimal flow conditions in every single case.

The energy supply part of the industrial energy system may, in some respect, be more alike from case to case. In general, the same kind of equipment is encountered, but in this part of the system a high accuracy level is important in the representation of the operating conditions of the units. The operating conditions may strongly affect the system cost. In this part of the system, energy supply units can often offer a choice, where different cost situations are valid. These options may as well affect the optimal

![Fig. 4. The fuel mix of the steam boiler represented in paper I.](image-url)
production level. One equipment unit, that involves the conditions of a specific industry, could be represented by several nodes. Examples of such representations are the complex fuel mix of a steam boiler in a pulp and paper mill (Paper I), or the operating strategies of a backpressure turbine, used in a refinery (Papers II and VI).

The steam boiler, described in Paper I, has a specific fuel mix at different output levels of steam. As is shown in Fig. 4, waste bark is used at the lowest output level, 0-36 MW. When the capacity reaches above 36 MW, the output level of waste bark is reduced to 30 MW, whereas the further increase in the interval 36-60 MW is reached by a mix of waste bark and bought bark in the proportions 1:3. At the same time, a constant fuel oil support of 6 MW is needed. Above 60 MW the output level is increased by the use of fuel oil.

![Diagram of fuel input and steam output](attachment:image.png)

Fig. 4. The node representation of a steam boiler with a complex fuel mix.

In the model, the fuel mix is represented by five nodes, see Fig.5. The addition of the output flows from the nodes 13-16 constitutes the total steam output from the boiler. The flow level is represented in each node with an upper bound, i.e. the sum of the upper flow levels in the nodes represent the maximum capacity of the steam boiler. Node 13 represents the use of waste bark in the interval 0-36 MW. At an increase above 36 MW, the nodes 15 and 16 are added to node 13. The fuel oil support, needed
in this interval, is included in the output from node 13. The mix of waste bark and bought bark is represented as a percentual aggregation of two flows in node 28, whereas the top demand for fuel oil is represented in node 14. The input flows of fuel to each node are multiplied by the fuel cost in the objective function. The cost for the constant fuel oil support is represented in the nodes 15 and 16 by an extra binary integer in each time step. If there is a flow of bark to the nodes 15 and 16, the cost for fuel oil support is included in the objective function, otherwise this cost is not included. In this way, the whole capacity area of the steam boiler is represented with a high accuracy in the industrial model.

Another example of increased node accuracy in the energy supply part of the system is the representation of the backpressure turbine at the refinery, described in Paper II. In this case, the backpressure turbine can be operated with or without medium pressure pass-out steam. In order to investigate the whole range of possibilities in the operational area, three operation alternatives are chosen for the representation in the model. The turbine can either be operated without pass-out steam, or with pass-out steam with the amount 0-10 ton/h or with the amount of 10-20 ton/h. The operation alternatives are optional. If it is obvious that the optimal operational area is found at a low amount of pass-out steam in all time steps, three new operation alternatives closer to the optimal point can be chosen. Non-linear relations between the energy flows are represented with good approximations by binary integers in piece-wise linear functions and in step functions. The performance of one equipment unit is here described by the use of eleven nodes.

4.2. Interconnection of energy and material flows

In industrial energy systems, the energy costs are sometimes lower than other production costs, but it is still important to find the optimal production strategy from the energy system point of view. Even when the product demand is approximately constant, the production flow level can sometimes be allowed to fluctuate within the limit of storage capacity and the availability of raw materials. The operating strategy of the industrial utility could be influenced by small changes in the production system. It is often possible to reduce the costs for electricity and fuel to some extent, even if the production flow level is restricted by other factors. Some restrictions can be represented in the MIND method by logical constraints or bounds for the production flow. Another way is to find the time division, that can reflect the proper production demand changes. As the time division can be performed in long term and short term time steps, it can be chosen to reflect the desired possibilities of a flexible production process. Input data for
the production demand can be given in the optimization as an average value over a longer time period. By the proper choice of time division, the optimal level can be found in each time step in relation to the average production demand. An optimization of the production level is performed in the Papers II - VI. On the other hand, when the production demand is clearly defined and no flexibility is desired, it can be stated as input data for each time step. In order to find the optimal production level, the interconnection of energy and material flows must be regarded.

In the optimization of a pulp and paper mill, Paper I, the results show that changes in the mix of raw materials will affect both the steam demand of the processes and the steam production capacity in the system. Wood is mixed with recycled fibres at three different levels, 25, 30 and 35%. The recycled fibres require less processing in the sulphate pulp mill than does the chipped wood. An increased addition of recycled fibres leads to a lower steam demand and a lower demand for chemicals. The recycling process for chemicals, performed in the soda recovery boiler, is also a steam production capacity in the system. A reduced chemical demand will thus reduce the steam production. A reduction of the steam production in this unit will require an increased production in other units, where the cost may be higher. It is obvious that, in this case, the interconnection of material and energy flows is imperative for finding the minimum system cost.

Electricity and steam demand is represented as a requirement, related to the flow level in each process node. The energy demand is often non-linear in relation to the material flow through the process units. A change of the flow level will affect the total cost of the system, since both the raw material costs and the energy costs are influenced. Non-linear energy functions reflect the variations of the energy demand as the production flow is changed. In Paper III, the interconnection between the energy and the material flows is studied at varying boundary conditions. The possibility to represent non-linear relations in a flexible time division is applied. The effect of the non-linearity in the electricity demand function at the real and at a calculated, theoretical tariff is investigated for three industrial cases. The theoretical tariff is calculated with the linear programming method MODEST for the municipality of Linköping, Sweden, by Backlund (1990). The price is calculated as the theoretical cost for electricity at a mix of production in existing equipment units in Linköping and purchase from the main utility company, Vattenfall AB, at each time period. The calculated theoretical tariff shows slightly lower energy prices than the real tariff. The cost difference is merely contributed by the larger peak demand charge of the real tariff. The comparison of the two tariffs represents the changes which could be achieved at a local price adjustment to the existing production system. As is shown by Andersson (1993), the cooperation between the producer, the distributor and the consumer of electricity will be mutually
profitable, when a correct pricing is applied. The price difference between the tariffs is recognized, in the optimization results of Paper III, as a lower system cost in the cases where the theoretical tariff is used. In Paper IV, a similar investigation is made. The production schedule, with optimal electricity demand, is calculated for three cases of energy demand functions, but in this paper a larger span between the linear and the strongly non-linear cases is applied. The energy charges of the theoretical electricity tariff is used with two additional cases of differentiation. The results from Paper III and IV show that it is profitable to change the production flow in accordance to the differentiation of the electricity tariff. When the relation between energy and material flows in the industrial system is linear or near linear, savings are always possible by shifting the material flow to low-price periods. If, on the other hand, the energy demand function shows a negative slope the opposite result is achieved, i.e. the optimal electricity demand is found when the material flow is shifted to the high-price period. These differencies in optimal strategy is achieved once there is a differentiation in the electricity tariff. The degree of differentiation will, naturally, affect the saving potential.

4.3 Comments on applied approximations

Since the minimum system cost is the objective of the optimization, all significant costs must be represented with the best possible accuracy. The electricity tariff is, for industrial high-voltage customers, sometimes a matter of negotiation. This implies that customers can have different subscription, demand and energy charges as well as different ways to calculate the demand and subscription levels. With the MIND method, such differences can be accounted for in the time division, the ordering of the time steps and the applied charges.

The subscription charge is based on the customers subscription for a limiting upper power level which, if exceeded, is imposed with a penalty charge. This is usually valid throughout the year, but other periods can also be defined. In case this limit is valid only during part of the year or when the limit is exceeded, the subscription charge may affect the optimal operating strategy and should be included in the optimization. The industrial cases of the enclosed papers have subscription levels that will cover for the process demand with good margins, and since the power limit is valid over the whole year, the subscription charge is not included in these studies.

The demand charge is applied for the peak hour during daytime in winter. This demand can be calculated in different ways. One way is to charge the average value of the three highest measured peak hours. In the MIND method, a separate time step can be included to represent the peak hour. It can also be chosen as the highest average
hourly energy flow at daytime during winter. In the latter case, the exact value of the peak load may not be reached but, depending on the circumstances of the study, this can be an acceptable approximation. In Papers I, II and VI, the results are presented as a difference in system cost between the optimal case and standard operation. This procedure will reduce the error, that lies in the approximation of the peak demand charge. In Paper III, the influence of the electricity tariff on the optimal production schedule is studied. The main objective of this paper is not the exact potential for economical saving, but the optimal production schedule at different nonlinearity of the electricity demand function. Therefore, the error involved in the peak demand approximation has been considered acceptable.

In Paper VI, the optimal operating conditions of the industrial utility and process systems are calculated by the MIND method, while a feasible heat recovery network was synthesized by Pinch Technology. The MIND optimization includes the flexibility of the encountered subsystems, with respect to changes in process and boundary conditions. The heat recovery network, on the other hand, is calculated for steady-state process conditions. The results from the Pinch Technology study are assumed valid for the ranges chosen for the production level in the MIND study. This approximation involves the heat recovery network operation at a constant efficiency over the whole range of production flexibility that is included in the MIND optimization. A further analysis would require a study of the efficiency changes of the heat recovery network at a change of the flow levels.

4.4. Possibilities to extend the application area of the MIND method

In the MIND method, electricity and steam flows are referred to as energy flows per hour (kWh/h). The actual temperature and pressure levels in the equipment units are included in the performance data, i.e. energy demand, fuel demand, efficiency etc. On some occasions it is, however, necessary to consider the temperature level of the flows, for example when heat recovery networks are studied. This means that heat integration cannot be included directly in the optimization procedure of the MIND method. Still, a heat integration study can be performed separately and then included as an option in the node network of the MIND method.

In paper V, a procedure for the combination of Pinch Technology and the MIND method is suggested and described. Pinch Technology is used to find the heat recovery possibilities in a heat exchanger network. A trade-off between the optimal energy demand and the optimal cost situation is found. In the heat exchanger network,
existing equipment can be rearranged, units may be exchanged or added to the network. Practical limitations in the application of the theoretical results are also considered. Pinch Technology can be applied to part of the industrial system or to the whole system, i.e. the application area can be chosen. The results from a Pinch Technology study can be integrated in the MIND node network. The combination of the MIND method and the Pinch Technology implies that energy saving measures can be investigated in conjunction with the operating strategy of the utility system and the production system, as well as structural analyses, where new investment alternatives are considered.

Paper VI describes the combination of Pinch Technology and the MIND method in the analysis of a refinery. The process system and the utility system are described in the MIND node network in the same way as in paper II. The results from the Pinch Technology analysis are included as two parallell process node options, representing the whole process system, including the heat exchanger network with and without a heat pump. The Pinch Technology study is concentrated to the possibilities to recover heat in the surroundings of three crude distillation units at the refinery. The three resulting heat recovery networks are added and included in a MIND process node, where the existing demand for electricity and steam, as well as the demand for cooling of the products, is influenced by a percentual change. In this case, energy recovery measures can be compared to investments in increased steam production capacity. The combination of methods facilitates the investigation of specific structures and flow options in the industrial system. Different alternatives can be compared on equal terms.

In cases where several near-optimal solutions of heat recovery networks can be found, they can be included as parallel node options in the MIND optimization. It is not only important to find the most efficient heat recovery network, but also to find the network configuration that is efficient in the whole flexibility range of the process system. The efficiency variation of a heat exchanger network can be included in the MIND method, as is shown in Fig. 6. The steam demand is represented as a function of the material flow for the original process line, and for two options of process lines including a heat recovery network. The fluctuations can be found within the material flow limits shown in the figure. The heat recovery networks represent two near-optimal solutions of the heat exchanger layout at a medium material flow. A change of the material flow will lead to different consequences in the two choices. In heat recovery network 1, the best efficiency is found at medium material flow, while a change of the
Material flow limits

Original process node

Process node +
Heat recovery network 1

Process node +
Heat recovery network 2

Fig. 6. Two examples of steam demand change at the introduction of a heat recovery network.

material flow will give a reduced efficiency. In heat recovery network 2, the best efficiency is reached at a high material flow, whereas a lower material flow will reduce the efficiency. The efficiency changes of the heat recovery network, which can be found in a flexible process system, can be included in the MIND method in this way.

An interesting view of the future use of the MIND method is the combination with other optimization and simulation methods, where the insight in the complexity of an industrial energy system can be further extended. The general approach in the representation of the industrial energy system in the MIND method provides excellent opportunities of combination with other methods.
5. CONCLUSIONS

The great variety of conditions, found in industrial energy systems, can lead to specific requirements regarding optimization methods. Either a method developed for a special type of industry or a method that can be applied to general industrial energy systems can be chosen. The MIND method is developed for general application. Generality can be achieved by the combination of existing possibilities in new solutions and by continuous development of the method.

In the modelling procedure of the MIND method, aspects of great significance are:

- a flexible time division,
- the choice of different levels of accuracy in parts of the energy system,
- the representation of energy and material flows in the process system,
- the representation of nonlinear relationships,
- a simultaneous representation of the whole system.

The MIND method is used for modelling structural and operational optimization problems. The time division can be chosen for each industrial case, that allows flexibility in the representation of the process system and boundary conditions. As the flexibility of the industrial utility and process systems can be simultaneously optimized, the interaction between them can be included. Energy recovery, achieved in heat exchanger networks, can be calculated by other methods, like Pinch Technology, and included in the simultaneous approach of the MIND method.

The representation of equipment units is performed in a general way, that allows the choice of accuracy level. Equipment units may be divided into several nodes that allow a better representation of the performance. This kind of representation is shown in Papers I and II, where a complex fuel mix in a steam boiler and the nonlinear flow conditions in a backpressure steam turbine can be included by the use of several nodes. Conditions, that are likely to affect the total system cost, should be included at a high level of accuracy. Other parts, where a low influence on the system cost is found, can be represented by fewer nodes. Equipment units can, for example, be aggregated to process lines or defined parts of process lines. This implies that the level of representation is optional in the MIND method.

The cost optimal operating conditions of the industrial utility system are closely related to the flexibility of the production level and energy recovery measures in the
process system. In this view, the relation between process energy demand and the production level becomes important. The representation of such relations can be accomplished in each process node by the expression of energy demand as a function of the material flow. These relations are often nonlinear, but they can be linearized in the optimization technique of MILP. Other nonlinear relations that can be found in industrial systems, are the energy conversion efficiency and the investment cost as a function of capacity.

The MIND method has been applied for industrial studies of the operating strategy of existing systems (Papers I and II) and for finding new equipment structures (Nilsson, 1990). These studies showed that substantial capital savings can be achieved when ordinary operating conditions, or the system structure, are altered. It is most difficult to foresee the effect of such changes without an optimization tool. Once a model of an industry is generated, the effect of changes in the boundary conditions or other input data can easily be investigated (Papers III and IV). The possibilities of recovering energy in the process system can be calculated by other methods and included in the MIND method. The procedure for the connection to other methods is simple and straightforward. Assuming a working period of three months for each of the studies described in Papers I and II, the capital savings at a change of operating strategy could give a pay-off time for the MIND optimization of two to eight weeks.

The MIND studies, referred to in this thesis, have been performed with similar time scales. The time division was based on the electricity tariff and changes in process and boundary conditions, for the representation of one or several years. This allows flexibility to be represented in order to act over the whole year. The interconnection of price changes, choice of fuel, production flexibility, on-site electricity production, capacity efficiency etc. can be achieved. Other time scales can also be chosen. An accurate representation of, for example, short term production changes would require a refined time scale. A calculation period of one week could include production alternatives, like schedules for change of product, sequences of batch processes, varying production demand, as well as variations in energy and raw material prices. The optimal operating strategy in response to short term changes can be achieved in this way. The strive in industrial production tends towards production at the right moment and to the right amount in order to reduce costs. The MIND method is adapted to the representation of various time scales. An interesting view is the exchange of data between the production control system and repeated MIND optimizations at different time scales, where both short and long term changes can be regarded.

In a future deregulation of the power industry, where spot prices and flexible energy rates can be expected, industrial energy customers will have increased prospects of finding profitable operating conditions. Demand side management and load
management will become increasingly interesting alternatives. As is explained by Björk (1987, 1989), electrical load management can be achieved by strategies like load priority, load shift, on-site electricity production, fuel choices, and storage of process media. Some of these can also be represented by the MIND method. Simulation methods for load management and manufacture planning and control can undoubtedly, like Pinch Technology, successfully be combined with the MIND method. In the environment of increased complexity, methods like MIND will be necessary for finding least cost operating and structural alternatives. Substantial capital savings can be achieved, when new investments and operating strategies are made in conjunction with the surrounding industrial system and suboptimal solutions are avoided. Conventional rules of thumb may not be valid for systems, where stable conditions and moderate energy prices are replaced by flexible conditions, like rapid price and demand changes.
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