# SIMULATION OF INDUSTRIAL ENERGY SUPPLY SYSTEMS WITH INTEGRATED COST OPTIMIZATION

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## ABSTRACT

Rational energy use in industry decreases costs, environmental pollution and depletion of resources. Since energy costs are often in the magnitude of the profit, a reduced energy use considerably affects the company-results. Yet, a systematic and profound analysis and optimization of the energetic processes is seldom conducted. In order to reduce the effort and increase the quality of energy system analysis, a computer aided method is being developed in a research project called TOP-Energy (Toolkit for Optimization of Industrial Energy Systems). The main goal of TOP-Energy is to support energy consultants in analyzing and optimizing industrial energy supply systems by supplying modules for documentation, simulation and evaluation of energy systems in respect to energetic, economic and environmental aspects. TOP-Energy consists of two major parts, a unifying framework and a set of modules: The former supplies the services of a modern GUI-application like module-sensitive dialogs and presentations, flow sheet editing and report generation. The latter are technical modules addressing particular aspects of energy system analysis like economical analysis or system simulation. An outstanding module of TOP-Energy is the supply system simulator called eSim, tailored to the consultant's needs. It evaluates energy supply concepts by means of historical or estimated demand data. In contrast to other simulator packages eSim supersedes costly modelling of control systems at an early stage of concept development by automatic optimization of component use. In order to model temperature sensitive components like chillers or heat pumps the conventional MILP-method was modified by employing evolutionary algorithms.
The article briefly presents the basic concepts of TOP-Energy including the framework's capabilities and then puts the focus on the simulator module, discussing its foundations and the solver numeric.
*Keywords:* Rational Energy Use, Energy System Simulation, Optimization, Engineering Framework, Object Model

## NOMENCLATURE

### Variables

| | |
|---|---|
| $A$ | Cross sectional area [m$^2$] |
| $c_{il}$ | Specific heat capacity of ideal liquid [kJ/(kg K)] |
| $\dot{H}$ | Enthalpy flow [kW] |
| $\dot{m}$ | Mass flow [kg/s] |
| $p$ | Pressure [Pa] |
| $\dot{Q}$ | Heat flow [kW] |
| $T$ | Thermodynamic Temperature [K] |
| $\lambda$ | Pressure loss coefficient [] |
| $\rho$ | Density [kg/m$^3$] |

### Indices

| | |
|---|---|
| $i$ | Vertice index |
| $j$ | Edge index |
| $k$ | Cycle index |
| 0 | Reference |

## INTRODUCTION

Today, energy savings and efficient use of energy are important means of sustainable development. Particularly in industry, an appreciable amount of primary energy can be saved by enhancing the existing energy supply and transformation systems. Apart from the possibility of avoiding energy losses due to deteriorated equipment and insufficient system control, a considerable amount of primary energy can be saved by designing optimized energy systems on the basis of techniques such as cogeneration, heat pumps and heat integration. For cogeneration, for example, this has been surveyed in [1]. Unfortunately, methods and supporting tools to find such potentials, for example exergy analysis and system simulation, are well known in science but rarely used in practice.

Since the costs of energy are frequently of the same magnitude as the company's profits, reducing energy costs can lead to an appreciable effect on the profitability of the company. On the other hand, any investment in the energy system of a company competes against investments in new products or production equipment. It has to be profitable over a short payback period, even though it is a long term investment. Furthermore, the high costs of expert advice with the risk of uncertain results are usually avoided. This leads to a situation in which significant potentials for saving primary energy and money are not employed.

For these reasons, it is desirable to take steps to reduce the efforts and costs of an analysis and subsequent improvement of industrial energy systems. The use of computer aided methods seems favorable for this task, as an integrated tool can speed up work and offer effective methods for system analysis and optimization. In addition, aspects usually neglected in decision processes, like environmental protection can easily be incorporated by an automated evaluation of appropriate coefficients.

These considerations lead to the development of a new modular designed software called TOP-Energy (Toolkit for Optimization of Industrial Energy Systems), which is developed by a cooperation of several partners from universities and industry.

## OBJECTIVES

The main objective of TOP-Energy is to provide an application that supports the process of energy system optimization for small- and middle-sized industrial sites. This work is usually done by smaller energy engineering companies that can not afford expensive custom developments. Contrary to numerous computational tools focusing on a specific technical problem, TOP-Energy integrates all steps of the typical work flow in one application, supplying a seamless flow of information from the first step of a project to the last. Apart from the support of computational methods like system simulation, special attention was paid to combining pure scientific methods with services such as comfortable user I/O and report generation. It is expected that this approach enhances working results by allocating appropriate computational methods, as well as reducing routine work by the automation of standard calculations and integrated project management.

## BASIC CONCEPTS OF TOP-ENERGY

The approach taken for the design of TOP-Energy is outlined by the a number of basic concepts incorporated into the application. The main objective of these concepts is to supply an abstract description of the processes and elements involved in order to transform the multiplicity of engineering requirements to a consistent and coherent application. The most important of them are briefly described below.

### Business Process Model

A business process model was defined in order to describe a standard work-flow for industrial energy system analysis and enhancement. It was derived from the German guideline, VDI 3922 (energy advisory for industry and trade) [2]. It describes a typical process for problem solution and is divided into three phases: problem analysis, solution development and decision. In accordance with this guideline a set of modules is defined each covering a major step in the work flow: A preliminary analysis module serves to give an overview of the energetic and energy-economic situation of the examined site.

This is followed by a detailed analysis where the goal is to document the energy supply system and identify its weak points in order to develop measures which enhance rational energy use.

In the solution development phase, a concept for an optimized system is found. For this purpose, TOP-Energy offers a system simulator designed for fast composition and simulation of energy supply system models. The result of the simulation contains various energetic, economic and ecological coefficients helping to evaluate the effects of the improvement measures planned.

Finally, to assist decision making, the developed variants are evaluated comparatively using one as a reference. For economical aspects, this is performed by an economy module capable of computing a variety of key figures directly from the simulation results.

## System Boundary Model

While VDI 3922 describes the engineer's workflow very well, it lacks a precise definition for system boundaries, especially the distinction between the energy supply system and energy utilizing systems. As this is vital for the interpretation of balance results and system coefficients, an appropriate definition is introduced in TOP-Energy. Basically, it distinguishes between four subsystems: First, the public energy market which represents the economic boundary conditions, supplying various forms of end energy to the examined site. Second, an environment based on the definition of a thermodynamical environment capable of exchanging energy and matter with the remaining two subsystems covering the examined site itself: The energy supply system and the systems of energy end users (usually the production site). The former converts the available forms of end energy into forms required by the end users. The latter employs the delivered energy in all kinds of technical processes, possibly rejecting waste heat or production residues to the energy supply system.

## Framework Approach

Analyzing the basic use cases of the application, it became apparent that every technical module requires certain functionalities that are non-specific to the technical problem it addresses: Basically, these are the persistent data storage and data exchange, user interface functionality like I/O-dialogs and flow sheeting, managing projects and report generation. In case these services are outsourced to a generic framework which exposes appropriate interfaces, the development of a module is reduced to the implementation of its technical contents. On the one hand, the availability of such a framework simplifies the transfer of a scientific program code to an engineering application tremendously. On the other hand, cooperation on the level of technical contents between framework, modules and component models, makes high demands on interface specifications and the underlying object model.

## Application Object Model

As the framework supplies services for persistent data storage and data manipulation on the user interface to the modules and model components, sophisticated interface specifications are needed. The foundation for these definitions is an object model describing the structure and semantics of data to be exchanged. Its central element – the component – is used to map real-world units, as well as to represent the usage of a module within the project tree.

A component can aggregate a set of different elements in order to store information about technical data, GUI appearance, network structures and report generation. First of all, components can contain other components and thus are able to build tree structures or collections. However, depending on the component sub-class, the aggregation of components is restricted. In order to map network structures like they occur in schematic representation of energy systems, components can contain connection points (*pins*) that can be connected to internal or external networks.

Components are not restricted to mapping real world objects to the data space, they may represent any configurable element of the application as long as it forms a complete and autonomous unit.

## Content Database

Closely related to the object model, a content database was developed in order to support the development of technical data structures: Using well defined technical terms when requesting user input or presenting results is vital to the usefulness of the application. Furthermore, developing a set of cooperating modules and component models requires a method to guarantee identical semantic interpretation of data by all communicating elements.

This is achieved by setting up a global dictionary of technical terms. In order to set up component data structures based on this dictionary, every definition of a technical term is attached to a pre-defined basic data type (such as *number* or *characteristic diagram*) including appropriate template data like units and value boundaries. These atomic data units – called *primitives* – can then be assembled to tree like data structures and be imported to a component template and thereby defining its data space. The unique definition of technical terms allows the save exchange of data between different modules even without exact knowledge of their data structures.

## THE TOP-ENERGY FRAMEWORK

Based on the concepts described above, an application framework was implemented, using the Computer Aided Schematics Toolbox (CASTool) developed by the R&D Department for Graph-based Engineering Systems of the Society for the Promotion of Applied Informatics (GFaI), Berlin.

The framework supplies the services of a modern GUI-application like module-sensitive dialogs and presentations, flow sheet editing for creating energy system schemes and report generation. Further more, the system provides a special editor that supports the buildup of component templates. Modules can be integrated into the application via a plug-in mechanism that allows the call of module code as well as the insertion of module specific menus.

A detailed description of the developed object model, the framework architecture and its capabilities can be found in [3].

## THE SYSTEM SIMULATION MODULE

TOP-Energy was designed to incorporate various computational methods implemented as plug-in modules. The most prominent one to be part of the first release of TOP-Energy is *eSim*, a module for simulation of energy supply systems. The main objective of this module is to determine a set of economic, energy-related and environmental key figures of an energy supply infrastructure for a term of usually one year. The boundary conditions of a system model are demand profiles for the different forms of energy as well as information about the environment.

### Overwiev

Energy system simulation is well known in science today. Various different solutions are available [4] although only few meet the usability requirements of engineering applications. Depending on the specific objectives of a simulation system, different mathematical approaches are used. The most sophisticated models base on differential equations (either DAE or ODE), being able to forecast the dynamic behavior of an energy supply system [5]. This, of course, requires a detailed modeling of the feedback control systems. Apart from that, detailed design data is required to calculate a machine's time constants. In a more simple approach, the inertia of the system components is neglected due to the fact that the time resolution of boundary conditions usually is not better than one hour. These quasi-static models result in algebraic systems requiring less detailed design parameters of the system components. However, the problem remains that control rules must be supplied by the user.

An approach that supersedes the specification of any control rules is to determine the system state by means of operation optimization. These systems, usually based on mixed integer linear optimization (MILP) [6], are frequently used to determine optimal power plant schedules [7]. However, this approach is capable of evaluating the design of energy supply systems too [8]. One drawback of these optimizing systems is the fact, that, due to the limitations of the underlying MILP, their models regard media temperatures to be independent from the system state, i.e. constant, or must be estimated before the linear problem is solved.

### Basic Concepts

eSim was designed to read network schemes created in the framework's scheme editor and stored in the format of the TOP-Energy object model. Figure 1 shows a simple scheme of an energy supply system created with the scheme editor.

While the component models are formulated using a modelling language designed to the specific numerical needs, the different network types are implemented in the simulator code. Currently these are electrical power lines, fuel distribution networks, hydraulic networks as well as nets modelling air and flue gas lines. Other network types e.g. for steam networks are currently under development. All network types except the electrical network are directed, each distinguishing input and output pins. Reverse flow in directed networks is not considered. As components may include other components in the object model, it is possible to design hierarchical simulation models. The lowest modelling level introduced defines a set of basic operations typical to the respective network type. These low level models can be thought as connectors between the network model and the modelling language. Examples are sources, sinks, pressure change and heat exchanging in hydraulic or combustion for air and flue gas networks.

The set of equations and algorithms describing the complete system model are assembled from the model descriptions of the single components and equations derived from the structure analysis of the connecting networks. While the network model based on components, pins and nets is the appropriate means to assemble, display and store energy network schemes, the structure analysis and the generation of balance equations is better conducted on graphs. Therefore the network description is transformed into a set of graphs, each describing one single coherent network with the vertices representing balance nodes and the edges describing a state change of the flowing medium through a component.

From these graphs, the equations describing the system can be derived. Besides the balances for mass and energy flows, a system of algebraic equations is generated in order to propagate constant parameters, e.g. medium properties, through the system.

## Time Step Algorithm

As eSim is thought to be used in an early stage of planning, modelling a system should not be too time consuming and require only data available to the user. Therefore, the operating optimization approach as described above was chosen.

This implies that the problem of modelling dependencies between fluid temperatures and component efficiencies has to be solved: When modelling a conventional boiler, it can be assumed that its efficiency is independent from the inlet temperature at every state of operation. To describe a hydraulic system of a set of such components, it is sufficient to formulate temperature independent energy balances regarding the all heat suppliers and consumers attached to the network.

$$\sum \dot{Q}_{network} = 0 \qquad (1)$$

Apart from that, it only has to be assured that the second law is not violated due to unappropriate temperature differences in the heat transferring components. However, assuming constant temperatures this constraint can be checked before the optimizing algorithm is carried out.

This is different if temperature sensitive technologies like condensing boilers, heat pumps or chillers are to be modelled. As the efficiency of such components depends on the inlet temperatures of their heat exchangers, temperatures cannot be assumed to be constant but must be considered as system variables. As a consequence, the equations of mass conservation have to be solved in addition to the energy balances. E.g. for a hydraulic network with no storage effects, this leads to equations 2 and 3 for each vertice and 4 and 5 for each edge in the network graph.

$$\sum \dot{m}_i = 0 \qquad (2)$$

$$\sum \dot{H}_i \approx \sum \dot{m}_i c_{il}(T_i - T_0) = 0 \qquad (3)$$

$$\dot{m}_{j,in} = -\dot{m}_{j,out} = \dot{m}_j \qquad (4)$$

$$\dot{Q}_j = \dot{m}_j(h_{j,in} - h_{j,out}) \approx \dot{m}_j c_{il}(T_{j,in} - T_{j,out}) \qquad (5)$$

In order to consider the pumping energy needed for operation of the hydraulic network using a simple pressure loss model, equations 6 and 7 occur for each edge and each cycle in the graph respectively.

$$\sum \Delta p_j = \frac{\lambda}{2\rho A^2}\dot{m}_j^2 \qquad (6)$$

$$\sum \Delta p_k = 0 \qquad (7)$$

Even under the assumption of an ideal liquid with constant heat capacity, products of two variables occur as well as squares of $\dot{m}$. Being part of the system to be optimized, the equations above introduce nonlinear constraints which cannot be treated with established algorithms like linear or even quadratic programming [6]. Being in need of a robust algorithm as well as integer variables for modelling switching events, ways had to be found to linearize these constraints. This would allow to treat the remaining problem using mixed integer linear programming (MILP) fulfilling the requirements stated.

Two approaches for the separation of mass and energy equations were found in literature: Filter [9] discretizes the mass flow variable by creating ”mass flow quantums”. This allows the formulation of both balances in one MILP system for the price of a high number of integer variables, causing a huge branch an bound tree to be calculated. Hackländer [10] separates the variables of the product by a binomial transformation. The remaining squares are then approximated by piecewise linearization. Though beeing very elegant, this approach as well introduces a huge number of integer variables in order to approximate three parabolas per linearized product. Moreover, the approximation leads to errors in the energy and mass balances depending on the quality of approximations.

In order to avoid a high number of integer variables in the MILP system, the approach proposed here separates the mass flow balances into a an additional system of linear equations and uses a special algorithm to coordinate the latter with the remaining MILP system. In the actual implementation, an optimizer based on evolutionary algorithms [11] was chosen, using the linearly independent mass flow variables as genome.

The principle of the algorithm is shown in figure 2. In order to create an individual of a generation, the optimizer chooses a set of linearly independent mass flow variables, either randomly at the beginning of the optimization run or by recombination and mutation from individuals of the parent generation. The set then is passed to a linear solver in order to calculate the dependent mass flow variables from the mass flow balances (eqn. 2 and 4). Finally, the complete set of mass flow variables is transferred to the MILP system, generated from the network energy balances and remaining constraints specified in the component models. As a result of the MILP solution, the target function value is returned to the optimizer in order to evaluate the relative quality of the individual compared to competing individuals.

As the mass flow variables are chosen stochastically by the optimizer, a relevant number of proposals will lead to a violation of constraints in the MILP system and therefore will end up without a solution. This occurs due to the fact that the vertice enthalpy balances (eq. 3) cannot be satisfied with the given set of mass flows. In order to return information about the proximity to a valid solution, a slack variable is introduced for each network graph vertice. Literally spoken, the slack variable represents a virtual enthalpy source or sink compensating the – otherwise invalid – enthalpy balance of the vertice. In order to let the slack variables converge towards zero during the optimization run, an accordant contribution is added to the target function, referred to as ”virtual target function” in figure 2.

Finally, the time step results including the energy and cost flows as well as the load of the components involved can be obtained from the MILP solution of the best individuum calculated.

In the basic implementation presented here, the calculation effort needed during a simulation is comparable to the algorithm proposed by Filter [9]. This can be ascribed to the fact that the mass flow values are chosen randomly by the optimizer and therefore a high number of linear systems has to be evaluated to find valid solutions of the energy balances. Though not implemented yet, a number of enhancements promise a relevant performance gain:

Evaluating the slack variables of the energy balances after a MILP run, information can be obtained about the local optimization direction in order to create better individuals. Passing this information back to the optimizer, a faster convergence of the time step algorithm can be expected.

As many load profiles show recurring patterns in practice, good starting individuals for the time step optimization can be obtained from previous time step solutions by a least square comparison of the respective system coefficients. This means is expected to speed up the time step calculation with increasing simulation time.

## Example Simulation

Figure 3 shows the results of a 48 hour cost optimized simulation run of the system shown in figure 1. The upper diagram shows the split of the heat load between boiler and cogeneration unit, the lower the customer generated fraction of the power demand. The power supply tariff distinguishes two energy rates depending on the time of day, marked by LT (low tariff) and HT (high tariff) in figure 3.

It can be seen that the operation of the cogeneration unit is driven by the heat load in the low tariff hours, feeding superfluous power into the public grid (see 5 a.m. of the first day). During the high tariff time, the cogeneration unit is controlled by the internal electric power demand. In case spare heat is produced, it is released to the environment via the emergency cooler (see 6 p.m. of the first day).

The example shows the capability of the simulator to optimize the system operation depending on the physical and economical boundary conditions given.

## CONCLUSIONS AND PERSPECTIVES

The main aim of TOP-Energy was the development of a software system to support the analysis and op-

timization of small to medium energy supply systems. Claiming cheap integration of additional computational methods and user-specific adaptability, a generic framework incorporating technical modules was developed.
In order to supply a simulation module for energy supply systems for the estimation of annual system efficiency and costs, a new algorithm was developed integrating the optimization of the component operation and therefore superseding the costly modelling of feedback control systems. Though the algorithm lacks of performance in the actual implementation, the feasibility of the approach could be proven.
Further development of the TOP-Energy framework will focus on the version control of component and module templates, an enhanced object model and report generation. Future development of the simulator will include the optimization of the actual implementation in terms of performance as well as the research on alternative coordination algorithms and additive network types and model components. Moreover, additional modules are under development, so a module for bench-marking energy demand and $CO_2$-emissions of industrial sites.
More information about TOP-Energy can be found on the project website at http://top-energy.ltt.rwth-aachen.de.


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## REFERENCES


[1] K. Lucas. On the thermodynamics of cogeneration. *Int. J. Therm. Sci.*, 39:1039–1046, 2000.

[2] Workgroup Energy Consulting. VDI 3922, energy consulting in industry and business. Technical report, VDI, 1998.

[3] E. Augenstein, G. Wrobel, I. Kuperjans, and M. Pleßow. TOP-Energy – computational support for energy system engineering processes. In *Proceedings of the 1rst IC-SCCE*, Athen, 2004.

[4] B. Elmegaard and N. Houbak. Software for the simulation of power plant processes, part A and B. In G. Tsatsaronis, M.J. Moran, F. Cziesla, and T. Bruckner, editors, *Proceedings of ECOS 2002*, pages 742–772, Berlin, 2002.

[5] S. Wischhusen, B. Lüdemann, and G. Schmitz. Economical analysis of complex heating an cooling systems with the simulation tool hksim. In Peter Fritzson, editor, *Proceedings of the third International Modelica Conference*, pages 259–268, November 2003.

[6] P.E. Gill, W. Murray, and M.H. Wright. *Practical Optimization*. Academic Press, 1982.

[7] K.-D. Maubach. *Mittelfristige Einsatzoptimierung in Versorungssystemen mit Kraft-Wärme-Kopplung*. PhD thesis, Bergische Universität-Gesamthoschschule Wuppertal, 1994.

[8] T. Bruckner. *Dynamische Energie- und Emissionsoptimierung regionaler Energiesysteme*. PhD thesis, Institut für theoretische Physik, Universität Würzburg, 1997.

[9] S. Filter. *Zur Modellgenauigkeit der mittelfristigen Einsatzoptimierung von Querverbundsystemen*. PhD thesis, RWTH, Aachen, 2001.

[10] P. Hackländer and J. Verstege. Optimierung der Betriebsplanung von Gasversorgungsunternehmen. In VDI Gesellschaft Energietechnik, editor, *Fortschrittliche Energiewandlung und -anwendung*, volume 1594 of *VDI-Berichte*, pages 605–614, 2001.

[11] Peter Roosen. Concept and application of the evolutionary parameter optimization toolbox EPO. In *1999 Proceedings of the ASME-Conference "Modeling and Simulation"*, 1999.

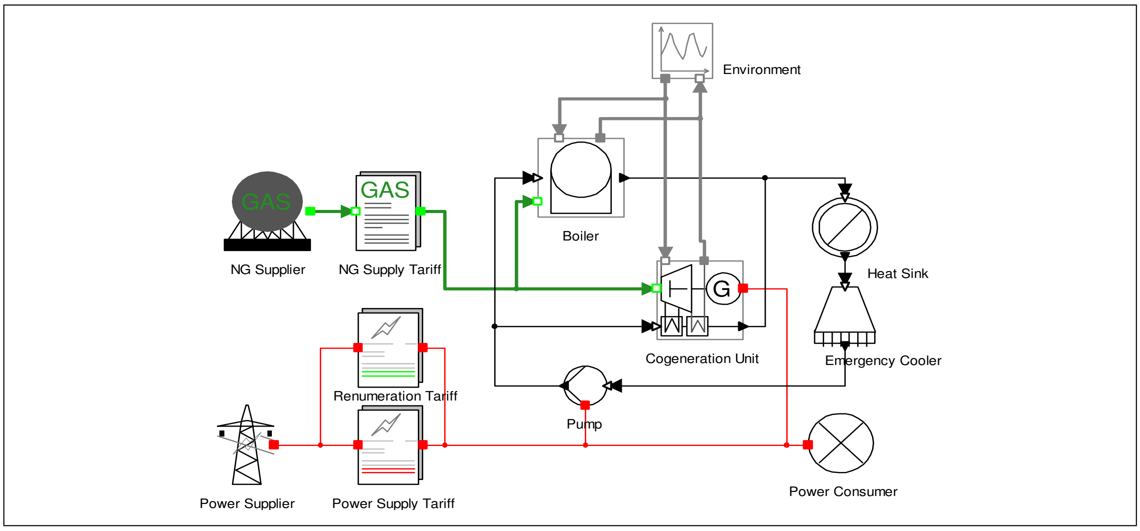


Figure 1: Example of a simple energy supply system scheme created with the scheme editor.

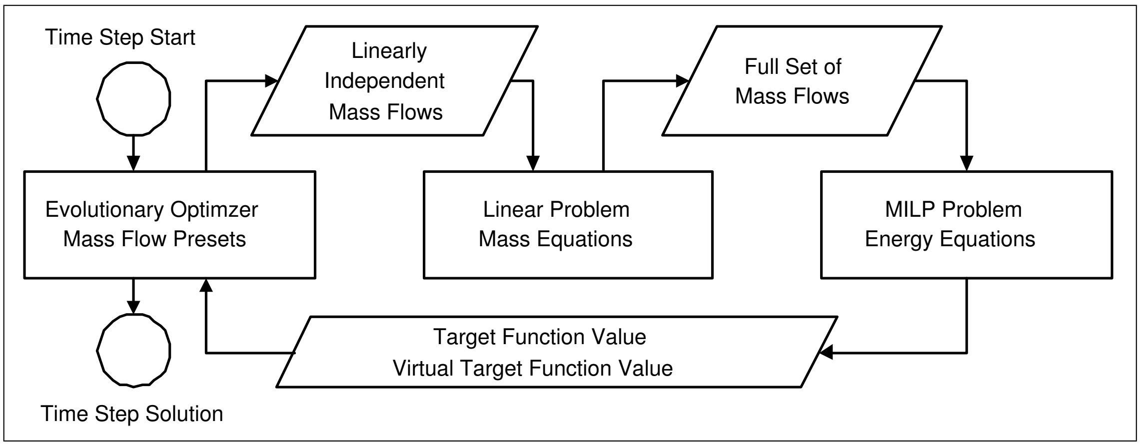


Figure 2: Principle of the proposed time step algorithm.

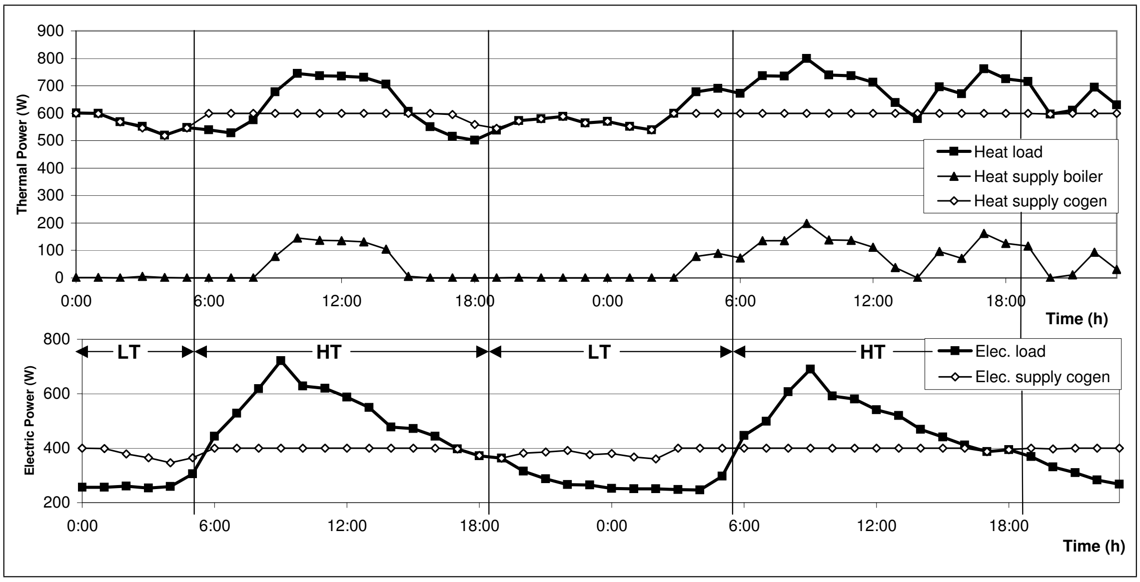


Figure 3: Results of a simulation run for the system shown in figure 1.