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Economical Analysis of Complex Heating and Cooling Systems with the Simulation Tool HKSim

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Abstract

Dynamic simulations of energy systems are essential when it comes to transient analysis and design of complex plants. Besides the choice of efficient subcomponents, like boilers, pumps or chillers, the control strategies have a large impact on the running costs of a cooling, heating or combined heating and cooling plant. This paper describes an applied simulation tool for heating and cooling systems. The economical benefits are discussed by means of a typical application: the simulation and optimisation of a complex industrial energy system.

1 Introduction

In cooperation with Imtech Deutschland GmbH & Co. KG (formerly known as Rudolf Otto Meyer GmbH & Co. KG and Rheinelektra Technik) a research project was conducted. The aim of the project was to develop a simulation tool, called HKSim [1, 2], for heating (Fig. 1) and cooling systems in building applications. This tool enables configuration studies and dynamic system simulations with time scales from a few seconds up to one year. For this purpose the simulation environment of Dymola [3], containing the object-oriented modelling language Modelica, is used to model complex heterogeneous systems. The graphical user interface, including the integration of Dymola and a data base for project management, was created by the department “Zentrale Ingenieurtechnik” of Imtech Deutschland while the model libraries [4] were developed at the Department of Technical Thermodynamics at the Technical University Hamburg–Harburg.

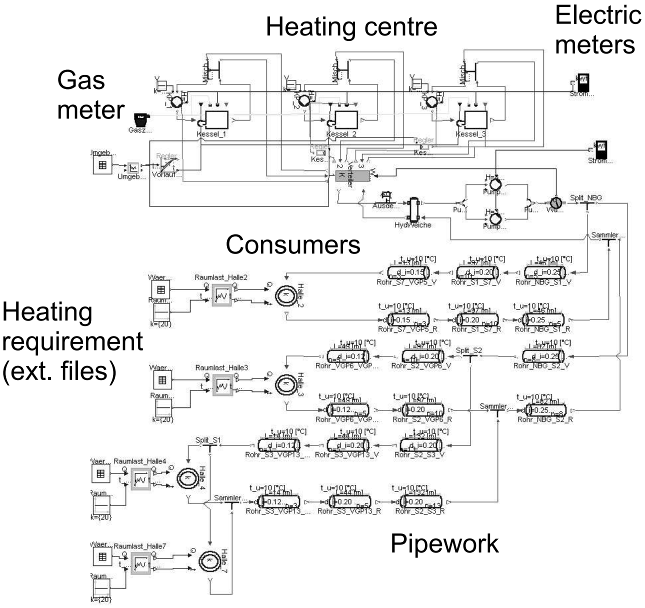

Figure 1: System schematic of a heating centre with distributed consumers and an earth–laid pipework

The component models are focused on the simulation of entire years. Therefore, the model equations have to be formulated as efficient as possible. The model design philosophy, which results from this important requirement, will be discussed in detail with respect to typical system components. The components can be mostly parameterised using manufacturer information or values resulting from own measurements. The handling of the models is primarily focused on users who want to use the models as they are provided or with alternative parameter settings. Expert–users are able to exchange model equations (e.g. models for

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medium properties, pressure losses and heat transfer) by means of replaceable models and develop their own components from the existing base classes. The boundary conditions of the system simulation can be supplied by data files from a building simulation or even measurement data.

Due to the separation of the building from the system simulation an efficient calculation for performance studies is realised when simulating complex plants.

The simulation tool HKSim was used successfully in several projects for the economical analysis of energy systems. In this article a typical project will be described, beginning with the selection of component models, followed by the consideration of individual control elements and determination of necessary boundary conditions. The last item usually consists of local weather data and calculated or measured heating and / or cooling requirement.

2 Current Library Content

So far, the most important components of cooling and heating systems have been supplied by the model libraries. All components are compatible by using identically defined hydraulic interfaces. Some elements which have been modelled and integrated into the libraries are [4]:

- normal, low-temperature and condensing boilers,
- cogeneration plants,
- consumers for heating, cooling and domestic water,
- pipes and storage tanks,
- splits and joints, mixing valves,
- controlled and uncontrolled pumps,
- heat exchangers [1],
- mechanical driven chillers,
- absorption chillers,
- cooling towers and dry coolers,
- special controllers (beyond: utilisation of Modelica's standard libraries [5]),
- electric and gas meter, oil supply.

Nevertheless, the development of new parts is continuing. In future, a model for different types of fuel cells will also be offered.

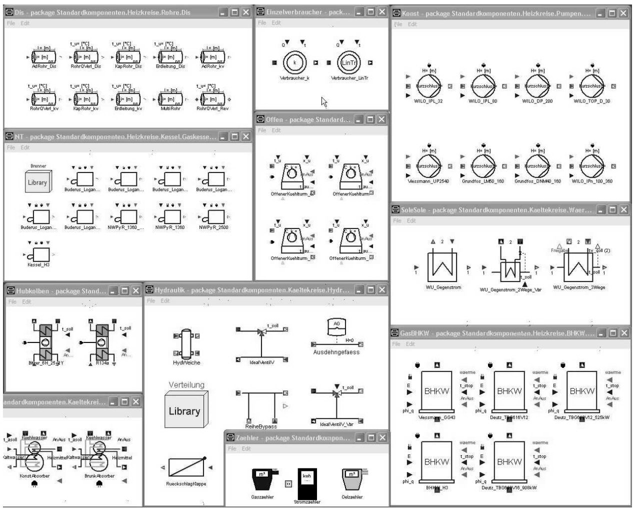


Figure 2: Screenshot of selected packages of typical heating and cooling components

In practice, it is important to have models with different levels of control and efficiency descriptions. Usually, a new project starts with the modelling of a system base layout. This first approach takes a lot of time because a correct understanding of the system's thermal and hydraulic behaviour is required. Generally, every single component which is part of the whole system should be modelled as accurate as possible. Unfortunately, this requirement contradicts most component manufacturers' information policies. Additionally, information of existing plants is often incomplete or not available. For this reason, models with a different depth of physical description are supplied by the libraries. For example, one can start with a boiler model which has a constant efficiency with the opportunity to replace it with a refined model later on.
For the user it is important, that the models use parameters, which are easily available or which can be determined without model knowledge.

3 Applied Thermal and Hydraulic Model Concept

The models are designed to enable a quick synthesis of plant models. This requirement is already considered in the modelling process in such a way that emphasis is placed on the calculation of the thermal behaviour. The hydraulic behaviour of a plant is not neglected but simplified in that direction, that the mass flow can be directly influenced at split and joint elements. The display of a transient pressure is not possible in favour of a fast and stable simulation. In combination with the concept of a load dependent simulation, designed to satisfy thermal loads, the calculation of the mass flow rate $\dot{m}$ is implemented in the model of the thermal consumers. Applying the first law of thermodynamics, the heat (or cooling) requirement $\dot{Q}_{build}$ of the building (or consumer, resp.) equals:

$$\dot{Q}_{build} = \dot{m} \cdot c \cdot (\vartheta_f - \vartheta_r) \quad . \tag{1}$$

If the feed temperature ϑ_f of the liquid and its heat capacity c is given two unknowns remain in this algebraic equation. By a second equation the dependency of the mass flow and the return temperature ϑ_r can be modelled applying heat transfer laws or measurement data. A simple but efficient approach is a proportional gain k of that mass flow rate, which is theoretically necessary to deliver the needed heat under the assumption of a perfect heat transfer ($\vartheta_r = \vartheta_{build}$)

$$\dot{m} = k \cdot \frac{\dot{Q}_{build}}{c(\vartheta_f - \vartheta_{build})} \quad . \tag{2}$$

The constant gain factor k may vary between 1 … 3. Another problem is that the mass flow rate should never be higher than the rated capacity of the installed pumps. In order to take this important limitation into account the rated mass flux of the pump $\dot{m}_{max}$ is added to the hydraulic interfaces (see Fig. 3). Furthermore, this value is divided at splitting elements with regard to the actual load $q = \dot{Q}_{build}$ of parallel consumers.

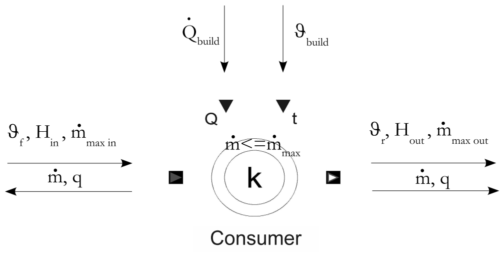


Figure 3: Input and output signals of the consumer model

In addition to this, the pumps head H must overcome the pressure losses of the plant. This is checked during an initial calculation assuming worst case conditions. The pressure check functionality is implemented in the model of an expansion vessel, which is also used as a sink for the algebraic signals (e.g. mass flow) in closed loops.

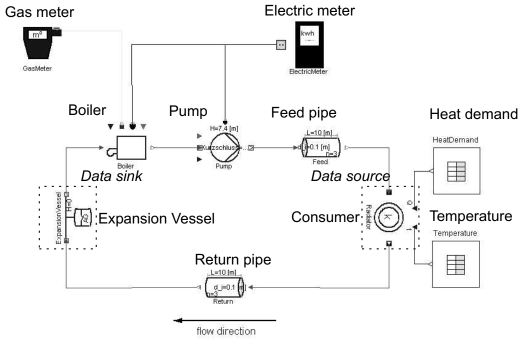


Figure 4: Simple heating plant

The base configuration for a simple heating plant is shown in Fig. 4. A minimum composition for a determined equation system must at least consist of the following three components:

- a consumer model for the calculation of a mass flow signal,
- a pump model for limiting the maximum mass flow rate and
- an expansion vessel which checks for a sufficient pump head (under worst case conditions) and avoids algebraic signal loops (e.g., mass flow rate).

Since the hydraulic simplifications lead to a heterogeneous data flow the user has to follow a few rules during the plant model generation. Those rules are visually supported by coloured interfaces which identify sources (triangle with black background), sinks (grey background) and neutral components (no background). Following the rules even complex plant models can be composed by the user without causing over- or underdetermined system models. Furthermore, some models must allow a flexible data flow due to numerical reasons. For example, the pump model can be switched into a mass flow source, when it is used in independent circuits without consumers. This is a common situation in complex applications where hydraulic bypasses are needed to realise a fail safe control strategy. By introducing a structural parameter it is possible to switch the model equations on demand. With regard to this feature on one hand and the connection rules on the other hand it would be very convenient for the model developer and the model user to have graphical annotations which can be controlled by structural parameters. Additionally, an update of graphical icons, when replaceable objects like interfaces are exchanged, would be very helpful.

To verify the used hydraulic concept, it was validated with measurement data from a complex cooling system displayed in Fig. 5. The chillers are shown on the left hand side of the picture including one conventional water chiller and two heat exchangers which are part of a chiller / ice storage circuit. The total capacity is 1,600 kW at a system temperature of 7°C/ 15°C. The cold water pump of chiller #3 operates with a constant speed in contrast to all other pumps, which are controlled. Therefore, a hydraulic bypass between the feed and return duct is necessary (see Fig. 5).

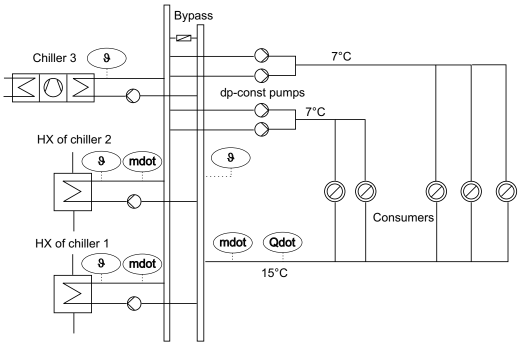


Figure 5: Schematic of the original plant and location of measuring points

As an input to the simulation the output temperatures of the chiller and heat exchangers were provided as well as the mass flow rates of the controlled pumps. Furthermore, the cold water mass flow through the buildings and the cooling requirement is known. Since the returning water's temperature is an important system variable it can be compared with the measurement to determine the quality of the consumer model description.

The corresponding system model to the description above is shown in Fig. 6. In this model the cold water temperature and flow is already merged to a single flux in the source model on the left hand side. A potential overshoot of cold water can be passed to the return side through the bypass. Moreover, the four feed pumps and five buildings are modelled as a single feed model with the same capacity since a local deviation cannot be resolved by the measurement data. The consumer model refers to the equations 1 and 2. The model can be adjusted rather easily by two parameters: the constant gain, which was set to $k = \frac{\vartheta_r - \vartheta_f}{\vartheta_{build} - \vartheta_f} = 1.75$ and the building reference temperature $\vartheta_{build} = 21°C$. The simulation was carried out with measurement data of one week during November with a peak load of approximately 530 kW and base load of 300 kW at the weekend (16th and 17th of Nov.).

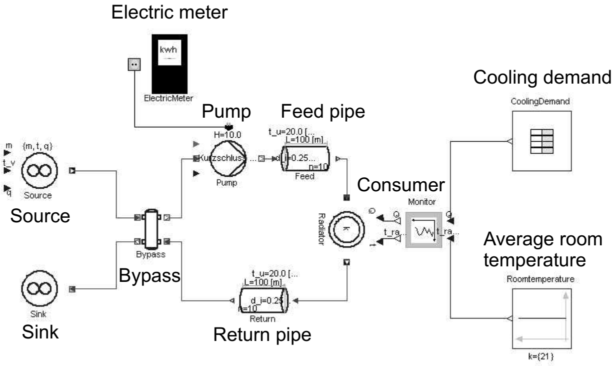


Figure 6: Modelica model of the cooling plant

Comparing the temperature of the returning water after the bypass in Fig. 7, a very good agreement with the measured values can be found. Some very few exceptions are due to the lack of information about the exact switch off times of chiller #3. Here only the output temperature was available. Instead, it was assumed that a cold water temperature of more than 7°C indicates a turned off chiller. Knowing that the water temperature during operation usually varies between 6.0 and 6.8°C and the outlet temperature due to a good insulation increases from 6°C to 20°C in more than 2 days, the temperature deviation shown in Fig. 7 can be explained.

The validation of the mass flow rate shown in Fig. 8 reveals that this value depends strongly on the cooling load. Obviously, there are periods where the agreement of measurement and simulation is very good but on some days there is a higher deviation. In a sensitivity analysis it was found that the building reference temperature of $\vartheta_{build} = 21°C$ may have a large influence on the mass flow rate. Especially, Nov.

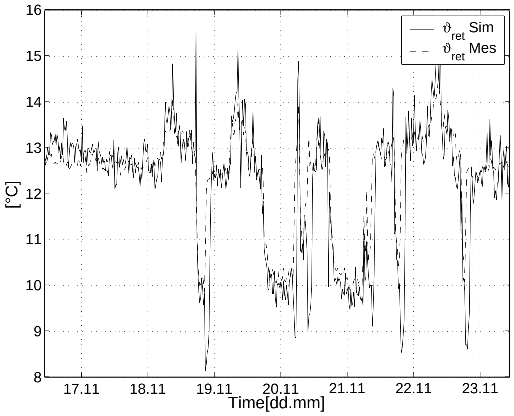


Figure 7: Comparison of the return temperature

19th and 20th were colder days (<0°C) in contrast to the 22nd which had a higher ambient temperature (4°C). Hence, it can be suggested that the unknown average room temperature was not constant during the measurement. Changing the temperature by 1 or 2°C gives the right mass flow rate.

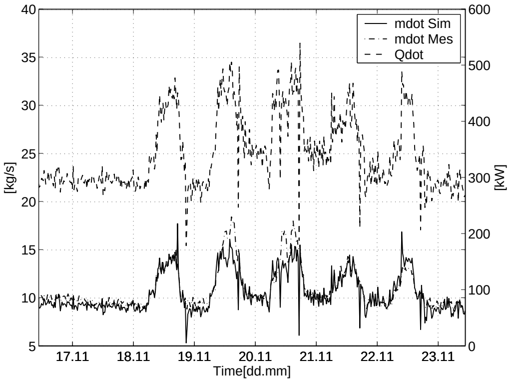


Figure 8: Cooling requirement and comparison of the water mass flow rate

It should be pointed out that the consumer model presented in this paper though it is based on a very simple approach can predict the mass flow and the return temperature with a sufficient accuracy. In addition to this, it enables a very fast model generation and simulation with computation times of a few seconds for a whole year. The model is also equipped with an overload routine which enables stable simulations when the heating and cooling capacity is too small for peak loads. In such an event the lack of energy will be compensated when the demand decreases again. A flag variable indicates that the plant's capacity is not sufficient.

4 Simulation of a Complex Industrial Energy Supply System

Within the development of an innovative energy supply system for a production facility the simulation tool HKSim was used to analyse the efficiency of the design concept and the running costs. After the simulation of the original layout optimisation measures were developed to increase the economical and technical efficiency.

The plant produces heat for the production lines, the heating system and the domestic hot water supply. Cold water is needed for industrial cooling processes and for air conditioning. The total cooling requirement reaches a maximum level of 2.6 MW in summer. The main idea behind the given plant schematic in Fig. 9 is to save primary energy by reusing as much waste heat as possible. Therefore, the heat needed for the periodic production processes is recovered and the superheat of the refrigerant after the compressor and the superheat of the compressed air is also transferred to the heating system. To ensure a minimum feed temperature a steam heat exchanger is implemented as a backup heat source. For cooling purposes, the continuous fresh water supply for steam production and domestic use is treated as a heat sink.

Since the continuous operation of the production lines has the highest priority it has to be ensured that the production lines are supplied with a sufficient amount of cooling water independent of the actual heat demand of the associated heating system. Hence, cooling towers with a large capacity were installed as a backup. Two of the three existing cooling towers can be switched between cooling of production lines, air compressors and chillers or free cooling of returning cold water to increase the average utilisation. The water of the cooling system is stored in two parallel tanks with a capacity of 700 m^3.

The following questions and tasks were identified and should be clarified by means of the system simulation:

1. How much heat can be recovered to decrease the additional heat input for the facilities heating? A coverage of 70% by waste heat would allow a cheaper building insulation with regard to German regulations.
2. Which inexpensive optimisation measures could help to realise a further reduction of running costs?

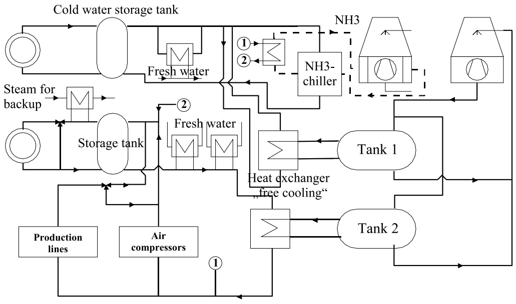


Figure 9: Simplified schematic of the original plant concept

Starting with the modelling of the original schematic displayed in Fig. 9 the plant model is divided into three supermodels (modules): the “heating module” (shown in Fig. 10), the “cooling module” integrating the cooling towers and the “cold water module”. The model of the heating and the production heat recovery system consists of eight different consumers (1), a boiler model representing the backup steam heat exchanger (2), four heat sources standing for the production heat recovery (8) and a number of hydraulic interfaces to the two other modules (4, 6, 7). The modules are connected in a supermodel. The reason for dividing the plant into subsystems is that the schematic is much clearer and the graphical update of Dymola works quicker, too.

After the model generation all necessary boundary conditions have to be determined. This data set includes the ambient temperature and humidity which is provided by a test reference year of the corresponding region in Germany. This fundamental input is also used in combination with the known rated loads to derive the thermal demand profiles for the air conditioning and heating with a simple linear approach. By means of measurements carried out on the existing production processes the possible heat recovery was determined and implemented using table interpolation models. The production processes can be described by a characteristic, transient heat output (Fig. 11). As a result from that fact, the outlet temperature of the heat exchanger’s cold side varies between 45 and 95°C during a period of a few minutes.

Based on a simulation of the original plant layout, potential modifications for an improved performance are determined, regarding the hydraulic circuit and governing control of the plant and its components:

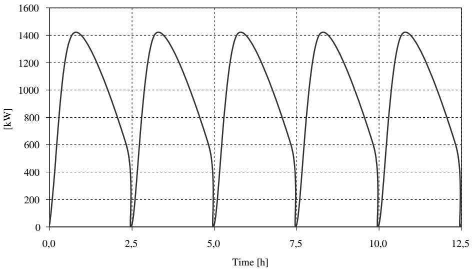
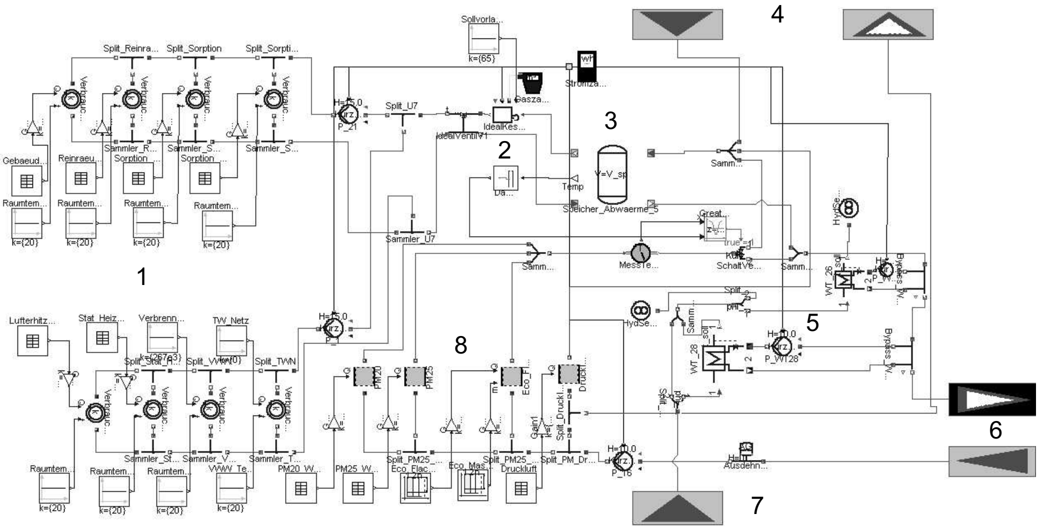


Figure 11: Periodic heat output of one production process

- **Modification 1**: All heat exchangers connected to the return side of the cold water storage tank are connected to the return side of the cold water consumers, whereby the heat exchanger’s input temperature is increased since the mass flow of the chiller pumps is always higher than the mass flow of the main pumps.
- **Modification 2**: A fixed periodical day / night switch of the cooling towers is replaced by a temperature dependent control to account for a changing level of primary cooling demand of the production lines. This measure shall increase the free cooling capacity, when more heat is transferred to the heating system.
- **Modification 3**: Cooling water with a temperature level below the desired value of the feed temperature is hydraulically connected to the cooling heat exchangers.
- **Modification 4**: The set point of the heating feed temperature is dependent on the actual heat demand and can be decreased if high temperatures are not necessary.

The simulations of the actual and the modified layout are carried out with identical boundary conditions and except from the modified parts the models are identical. The reference system for the economical analysis is a non-coupled heating and cooling system without heat recovery. All modifications are investigated separately as well as combined, since their impact may show a compensation effect in the coupled system. The investigation is focused on the possible savings of natural gas, which result from the demand of heating and domestic hot water with variable heat recovery.



Legend:

1 Heat consumers
2 Backup steam heat exchanger (boiler model)
3 Hot water storage tank
4 Hyd. interface to module “cold water”
5 Service water heat exchangers
6 Hyd. interface to module “cooling water”
7 Hyd. interface for service water from module “cold water”
8 Heat recovery from production processes and air compressors

Figure 10: Modelica model of the heating module

Fig. 12 reveals the development of the primary energy consumption for the conventional system (the steam exchanger covers the total load), the original layout and the optimised system. Since the total heat demand is 9,546 MWh and the original concept is only able to cover it with not more than 38% waste heat the first requirement is not satisfied with this approach. The situation changes when the plant layout is modified in the way described above. Now, the heat recovery contributes more than 80% to the heat load which is sufficient enough to reduce the compulsory thermal insulation of the associated buildings. The total savings of gas needed for backup heating by the steam heat exchanger sum up to 148,000 EUR in one year regarding the difference between the original and final layout. This corresponds to 4,000 MWh (-68%) less heat supply at a heat price of 37 EUR/MWh. This moderate price results from experiences of the plant owner and also considers costs for maintenance and amortisation of the devices.

Comparing the remaining cooling load of the chillers before and after the optimisation one can determine an increased coverage of the cooling demand (15,445 kWh) by the cooling towers from 3.1% to 15.8% compared to a separated conventional heating and cooling plant. This result can be explained by the enhanced free cooling, especially during winter, spring and autumn (Fig. 13 and 14) since the return temperature is higher and the operation time of the cooling towers in free cooling mode is prolonged.

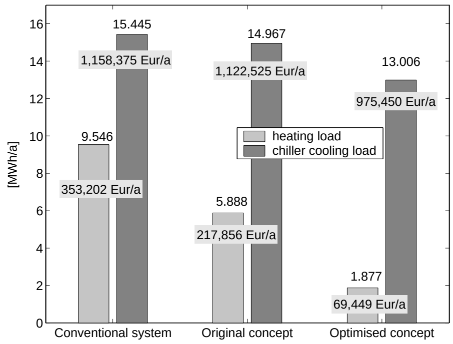


Figure 12: Development of the primary energy consumption for heating and cooling and reduction of running costs for the conventional separated system without heat recovery, the original concept with heat recovery and the optimised plant

It has to be emphasised that this study in this depth was only possible by means of transient simulation which enables the display of the temperatures throughout all components under consideration of the thermal capacities. This unique feature of a dynamic simulation is one advantage when the temperatures have a large impact on the efficiency of the process (i. e. the COP of chillers, denoting the quotient of the cooling capacity to the electric power consumption) and dominating capacities are characterising the energy system (i. e. storage tanks). A static simulation is not able to consider these important effects.

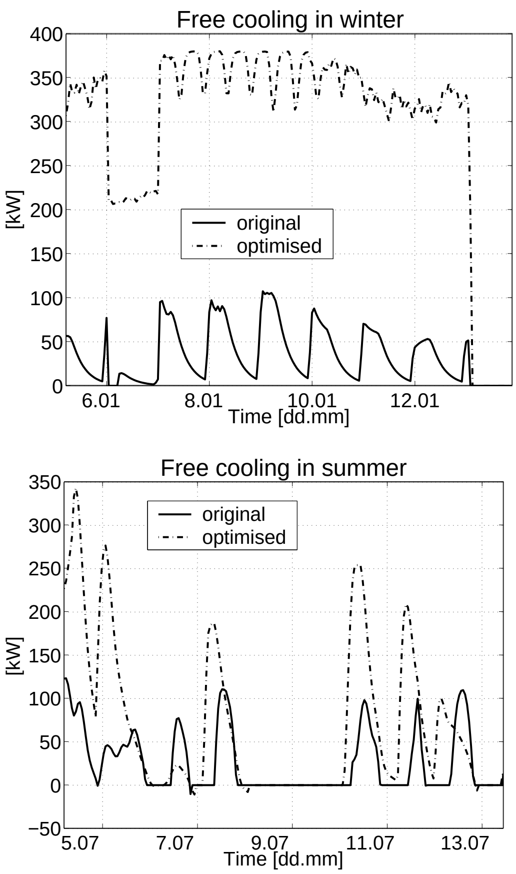


Figure 13: Cooling impact of the heat exchanger for free cooling in winter (t.) and summer (b.) - optimised plant including all modifications

The remaining cooling load of each calculation is multiplied with a fixed cooling price of 75 EUR/MWh resulting from experiences of the plant owner, again. The original concept could already save 36,000 EUR/a. Taking all modifications of the optimisation into account the costs could be drastically decreased by 183,000 EUR/a. These cost reductions are mainly due to the optimisation of the free cooling heat exchanger position. The plot of the heat, transferred by the free cooling heat exchanger, is shown in Fig. 14.

Regarding the economical effect of the simulation, it is evident, that the optimised plant layout can save 295,000 EUR/a in comparison to the original concept and more than 465,000 EUR/a if the plant would have been built in a conventional way without heat recovery. Apart from the costs for the changed piping the modifications of the optimisation do not require expensive components.

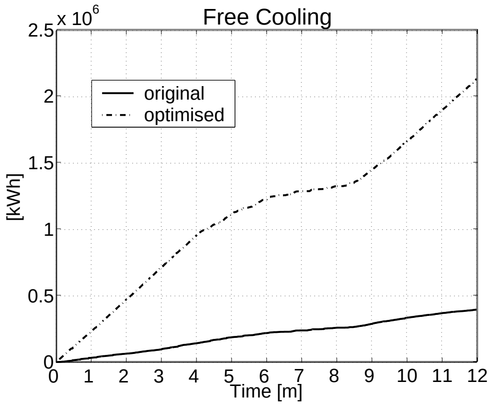


Figure 14: Amount of free cooling - optimised plant including all modifications

The computing time for a year time simulation of the original model and the optimised model are in the range of 10 to 24 hours depending on the installed processor.

5 Conclusions

This article is dedicated to the transient simulation of complex energy systems like they appear in large buildings and industrial plants. For this purpose a simulation tool, called HKSim [1, 4], was developed by Imtech Deutschland GmbH & Co. KG and the Department of Technical Thermodynamics of the Technical University of Hamburg–Harburg. It was pointed out, that such a tool is capable to simulate even complex systems. The computational effort can be justified by the prevention of possible failures in system layouts and estimation of possible savings, which are of economic interest as could be shown in the described optimisation. In the carried out simulation of the industrial plant the savings will pay back the investment in a short period of time.

In addition, a model of a thermal consumer was presented, which is necessary to integrate the heating or cooling demand from an external file into the system simulation. The model is designed for fast model generation and simulations of whole years and it predicts the mass flow rate and the return temperature with a good agreement to measurement data.

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