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Solutions to reduce energy consumption in the management of large buildings

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ABSTRACT

The building sector consumes, even today, about one third of primary energy used in countries like Germany, which, in addition to tons of CO_2 and depletion of energy sources, involves a cost of millions of Euros. This paper shows how, only through the optimization of the system technique regulations, energy savings by a margin of 30% can be achieved in offices and administrative buildings. This potential reduction or even elimination of expenses is possible with the use of the automation system that is proposed in this article.

It is important to emphasize that simulation models of HVAC systems and rooms are very often used during the planning phase of a project for a proper system design. However, these simulation tools offer additional possibilities for control algorithm development and performance observation which are not used in practice so far.

This article demonstrates that simulation based predictive control, using a system operation that is not depending on a main computer but on the components of an intelligent bus, offers the opportunity of a better utilization of the buildings and their thermal mass.

1. Introduction

The proliferation of energy consumption and CO_2 emissions in the built environment has made energy efficiency and savings strategies a priority objective for energy policies in most countries [1].

Buildings account for 30%–40% of the total primary energy use globally [2], and the building sector offers large potential to reduce primary energy use and CO_2 emission by e.g. reduced heating demands, increased efficiency in energy supply chains and greater use of renewable resources for materials and fuels. Several strategies can be used to realize this potential, including energy efficiency requirements in building standards, for example requirements that specify minimum energy efficiency for buildings. Improved building energy efficiency is a priority issue in the European Union (EU), where the building sector accounts for the largest share of the total primary energy use [3,4].

The energy consumption of an office or commercial building during its operational lifetime is usually significantly higher than the energy embedded in the materials and construction. For instance, a 60-building case study of commercial buildings by Lawrence Berkeley National Laboratories showed that 50% of the buildings had control problems [5]. Analyzing the savings through operation and maintenance in 132 further buildings demonstrated that 77% of the savings were obtained by correcting control problems [6]. Energy savings in such buildings are usually in the range of 10%–25%, and sometimes reaches 44% [5]. This demonstrates the need for detailed performance observation in such buildings. However, energy management in the building sector, in most cases, still a simple collection of energy consumption data for heating cooling and electricity on a monthly or annual basis. For heating energy consumption a degree-day normalization method (e.g. German standard VDI 2067) is used to average out the influence of varying weather conditions and to allow a better comparison of the heating energy consumption of different years [7]. For electricity consumption and cooling energy consumption such a simple normalization method does not exist. Furthermore, this backward looking method only allows the detection of variations in energy consumption over quite a long time period and the reasons for such variations in energy consumption is very difficult or nearly impossible to detect.

For a more dynamic energy management during recent years attempts were made to integrate the collection of energy consumption data into the building management systems (BMS). BMS are most common in large buildings and its historic core function is to manage the environment within the building. The BMS is typically responsible for the control of heating and cooling systems and air handling units that distribute air throughout the building, and local control of the heating and cooling mixture to achieve the desired room temperature. Sometimes a secondary function is to monitor the level of human-generated CO_2, mixing outside air with waste air to increase the amount of oxygen while also minimizing

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Nomenclature

BMS	building management system
COP	coefficient of performance
DDC	Direct Digital Control
ETFE	ethylene tetrafluoroethylene
g	energy transmission, from the German Word Gesamtenergiedurchlassgrad
HVAC	Heating, Ventilating and Air Conditioning
IP	Internal Protocol
LAN	Local Area Network
LON	Local Operating Network
OPC	Open Process Control
TAC	thermal activation of the components
TCP	Transmission Control Protocol

heat/cooling losses. Systems linked to a BMS typically represent 40% of a building's energy usage and if lighting is included, this number approaches 70%. The BMS is therefore a critical component to managing energy demand. An improperly configured BMS with control errors can easily increase the energy consumption of buildings in the region of 5%–30% – in some cases even more [8,9].

The main bottlenecks for an efficient energy management within building management systems are still the poor possibilities for graphical performance visualization and the cumbersome handling and analysis of measured performance data. Furthermore, the external use and exchange of data measured and collected within the local BMS is still difficult and in some cases nearly impossible.

As part of this project, the Technology Centre of Festo (hereinafter referred to as Festo TC) is analyzed in detail. Fig. 1 shows the company's headquarters in Esslingen Berkheim, Germany. The core topics of the research are energy distribution, TAC, the concept of artificial light, including daylighting systems of the facade and the system technique for HVAC. The building was created with the main aim of reducing energy consumption under the given architecture and to limit design requirements to a minimum. This should achieve a minimized absolute consumption, and secondly, an overall consumption with the least possible amount of primary energy. Both approaches were implemented by selecting the appropriate components and equipment in the engineering design and building as well as through the use of an intelligent multifunctional automation system. The project focuses on building management optimization, based on the simulation with the aim to reduce the energy used for the HVAC system. Here several methods are presented, which use equipment and building simulation of the used energy. Through these methods building systems consumption can be reduced by more than 30%.

2. Building, energy concept, and automation

Buildings with innovative technologies that results in very low operation energy use are being developed and may constitute a critical part of efforts to reduce fossil fuels use and CO_2 emissions [10,11].

2.1. Construction of the building

The modern comfort living conditions are achieved at the cost of vast energy resources. Global warming and ozone depletion and the escalating costs of fossil fuels over the last few years, have forced governments and engineers to re-examine the whole approach to the design and control of building energy system [12]. Consequently, it is of great importance in the building field to reconsider the building structure and exploit renewable energy systems, which can minimize the energy expenditure and improve thermal comfort [13].

The Technology Centre building is divided into three V-shaped building (Fig. 2). Each V has two "fingers" and the six "fingers" of the building are connected on the north end. The two main entries are also located on the north side, each between the central V and an outer V. Each V has an atrium between its fingers, which has a roof and a slightly sloping facade. The spaces between the Vs are free.

Each one of the six fingers has a technical room in the basement and are connected together underground through the service tunnel. In this tunnel are located the common systems, HVAC, electricity and air pressure, and it is also a pedestrian connection between the 6 fingers and the main building of the company. The technical trenches (large pipes) are near the stairs. The foundation of the building includes approximately 380 energy piles. The whole building, except the atriums, has false floor providing a space 60 cm in height for all the technical equipment of the building [14,15].

2.1.1. Building envelop, building facade and roof construction

The exterior facade of the office building is entirely made of a high quality glass (3 layer thermal insulation glass with a high value of thermal insulation and energy transmission, which is denoted with the letter g, from the German name: Gesamtenergiedurchlassgrad). Emphasis was placed on the high air tightness of the facade. The exterior facade of the offices has external blind for sun protection. The insulation of the roof rests on a metal layer, and under this layer there is a cavity for the TAC. The facade of the three atriums has a double layer glass. Each has a shading system installed. The roof of the atriums is formed by padded sheets and the arc is mounted on a support structure. The padded sheets are under pressure and can be pneumatically conditioned to either shade in or not.

2.1.2. Physical values of the construction of the office area and atriums

2.1.2.1. Offices exterior facade.

- Overall heat transfer coefficient of the glass: $U = 0.7\,W/m^2\,K$.
- Overall heat transfer coefficient of the facade (glass + construction): $U = 0.8\,W/m^2\,K$.
- Total energy transmission with the opened external blind: $g = 60\%$.
- Total energy transmission with the closed external blind: $g = 10\%$.

2.1.2.2. Offices area roof.

- Overall heat transfer coefficient of the roof: $U = 0.19\,W/m^2\,K$.

2.1.2.3. Offices area floor.

- Overall heat transfer coefficient of the floor: $U = 0.24\,W/m^2\,K$.

2.1.2.4. Atriums external facade.

- Overall heat transfer coefficient of the facade (glass + construction): $U = 1.45\,W/m^2\,K$.
- Total energy transmission with opened sun protection: $g = 46\%$.
- Total energy transmission with closed sun protection: $g = 20\%$.

2.1.2.5. Atriums.

- Overall heat transfer coefficient of the facade (pad + construction): $U = 2.7\,W/m^2\,K$.
- Total energy transmission with opened sunscreen: $g = 32\%$.

Fig. 1. Company's headquarters in Esslingen Berkheim, Germany.

- Total energy transmission with closed sunscreen: $g = 15\%$.

2.2. Building techniques

2.2.1. Sun protection for the offices facade

Intelligent blinds are used with light management function included, in order to control the amount of solar radiation (light and heat) into the building. A third part of the blind (upper third) is used to control the light, and the other two thirds are used to prevent excess light and heat [16].

2.2.2. Sun protection for the atriums facade

Sails are used; they operate with hydraulic rods, which are controlled by photosensors [16].

2.2.3. Sun protection for the atriums roof

Roofs of inflated sheets, controlled by photosensors, are used. The two positions (open/closed) are shown in Figs. 3 and 4. They consist of three layers of ETFE foil, the upper and middle layers are printed with a chessboard. The two patterns are printed so that they complement each other. If the middle layer ventilates upward shading occurs, otherwise the layer ventilates downward allowing the light to go through [17].

2.2.4. Production and distribution of heat and cold

The building does not have its own plant to generate heat, but the heating energy is supplied from the main building. Heating water for all consumers is distributed through the technology centres of the fingers. The required refrigeration is produced by three adsorption refrigeration machines. For cooling of the refrigeration machines three cooling towers are installed. When the outside temperature is adequate, the cooling towers can be operated in free-cooling, i.e., the produced cooling is directly supplied to the consumers [18]. Furthermore, the energy piles are used in the cold supply. The distribution of heating and cooling is performed by three supply distributors. Every two fingers is supply by one of the distributors. Means for heating, cooling and the free-cooling of the building are parallel to this supply and depending on the seasons

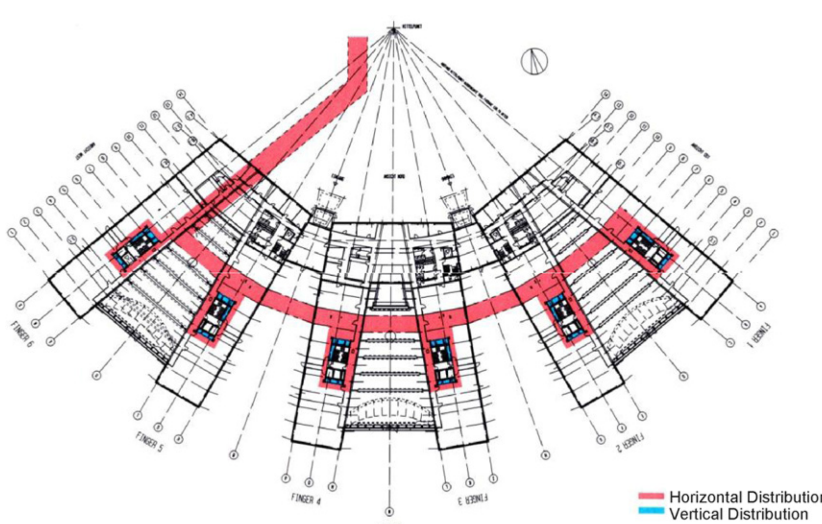

Fig. 2. Plan of technology centre ground floor and basement.

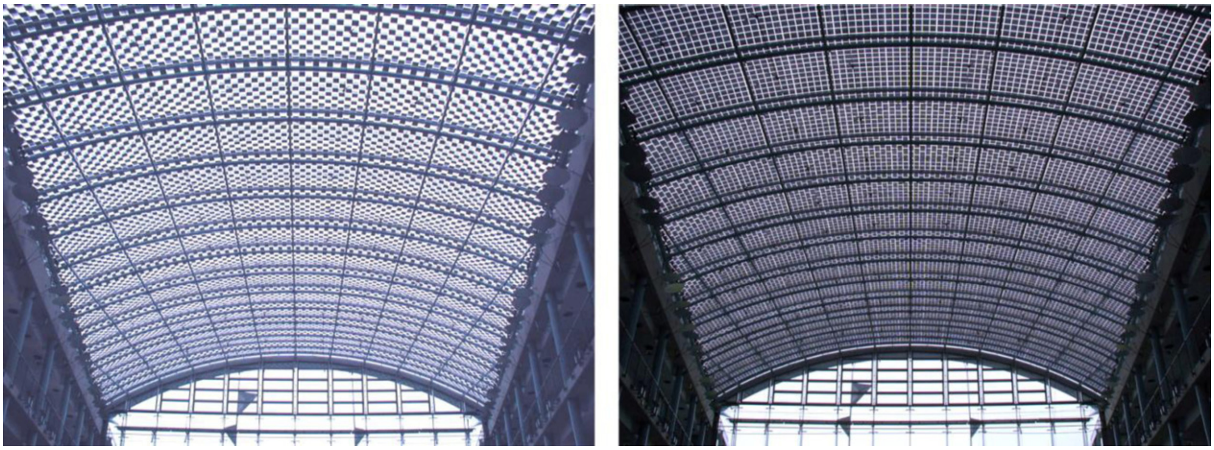

Fig. 3. Atriums roof, open (left) and closed (right).

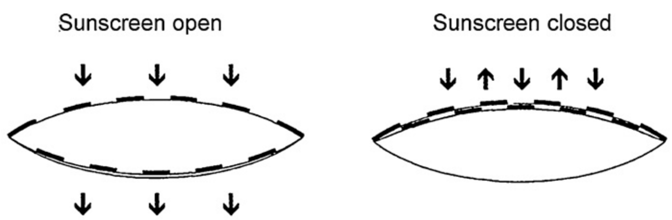

Fig. 4. Operating principle of the atriums roof, open and closed.

and the operating conditions of the building controlled by the control system of the building. The energy piles also provide energy in this distribution. From the supply distributors are supplied thermal activation of both heating and cooling as shown in Fig. 5.

The heating and cooling of the office areas is mainly due to the TAC. The TAC is installed in the ceiling of all levels, and the walls of the staircases. Inserting the tubes of the thermal activation is shown in Fig. 6. The individual loops of the TAC within a finger are connected together and share in common the temperature of the supplied flow. The various offices and meeting rooms are equipped with double bottom floor, where the equipment of refrigeration and heating is installed, in order to allow and individual climate con-

Fig. 6. Insertion of flexible hose for TAC.

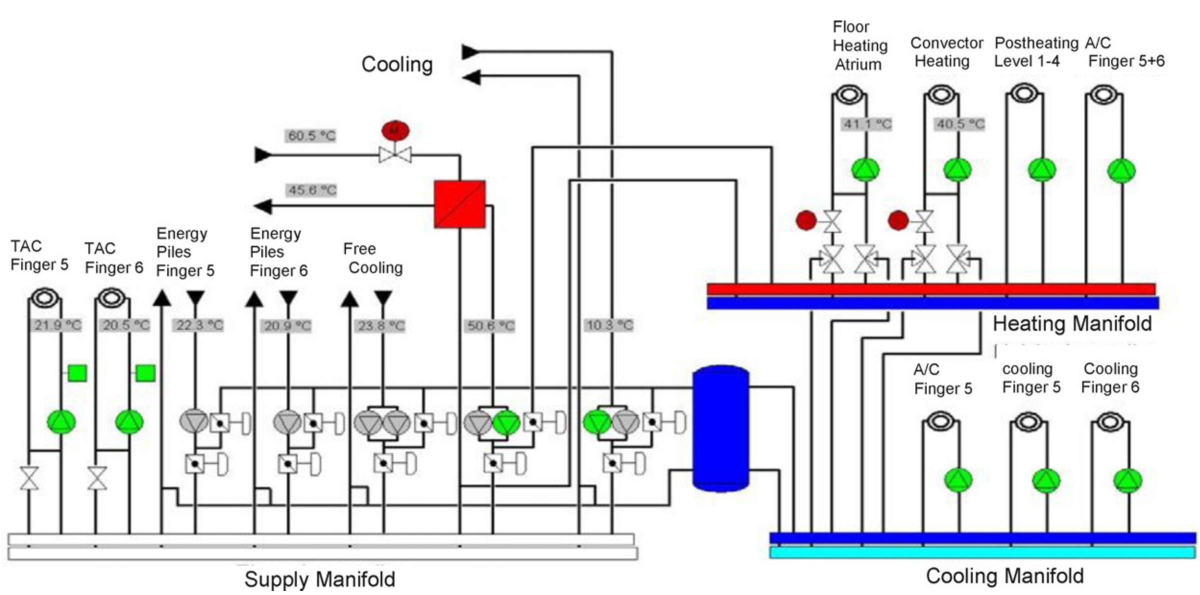

Fig. 5. Heating and cooling distribution.

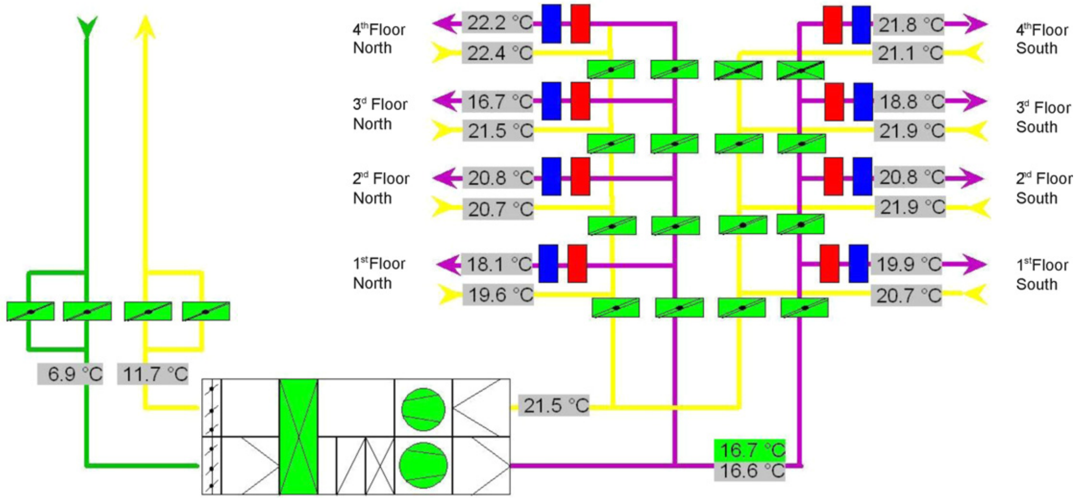

Fig. 7. One finger's ventilation diagram.

trol in every office. A system of heating and cooling by underfloor heating is used in the atriums [19,20].

2.2.5. Ventilation

Each finger has its own HVAC system. On the one hand, the system provides fresh air to common office areas, the individual offices and meeting rooms. On the other hand, it compensates the differences of temperature caused by different internal and external loads. The movement of both, the incoming and outgoing air, is done through the double floor with the help from a ventilation system. The system works only with fresh air and has a high efficiency heat recovery through a rotary heat exchanger, heating and cooling coils, via a variable-frequency drive drives the direct vent and a high-pressure humidification. To compensate the temperature difference in the office area, each floor in each finger is divided into two zones, so the whole finger is divided into eight zones. The inlet air temperature in each zone can be regulated with a heater or refrigerator at the required temperature in each area. Fig. 7 shows the schematic representation of the ventilation system of a finger. There is a HVAC system installed for the supply of fresh air for each atrium, which is equipped with a rotary heat exchanger of high efficiency, heating and cooling coils. The air supply is introduced through the apertures in the floor in the facade in the south side, the air extraction is carried out within the areas of galleries through the air intakes of the roof in every floor [21,22].

2.2.6. Lighting

The lighting in the office areas is carried out with auto dimmer lights (automatic control system that acts depending on the natural light conditions), each light is equipped with a sensor that is directly connected to the electronic ballast. The sensor monitors the light, depending on the ambient brightness, to an adjusted light intensity. Energy is saved with this automatic control whenever the natural light conditions do not require the aid of artificial light to achieve the desired intensity. The general lighting in the large office areas are fixed in groups of 4 intercepted lights. The lighting of these groups is switched on or off manually on a touch panel for employees as needed. Approximately, 20% of the lights are assigned to the passage lights. These lights are controlled through a time switching program. The lights are switched on in the morning, at a definite time and within a time frame, when the brightness is higher than a predefined parameter, they are switched off. By using the time frame the lights are prevented from being switched on or off during the day by a higher or lower brightness. Both, passage lights like all general lights, in the whole building will be turned off at night after 8pm by a central timer programme [23].

2.3. Energy concept

The building was created with the goal of reducing the energy consumption, in the given architecture and design requirements, to limit it to the minimum. This should get to reduce the absolute consumption to the minimum and secondly the fact that the consumption is covered with the least amount of primary energy. Both approaches have been carried out by selecting appropriate components and equipment in the construction engineering, and a multifunctional building automation system.

2.3.1. Energy demand reduction

The heat energy requirements of the building are reduced by:

1. Maximum use of free solar energy during the hot season through a glass with a solar factor of 60%.
2. Reduction of heat transfer loss through the glass. Value of heat transfer coefficient $U = 0.7\,\mathrm{W/m^2\,K}$.
3. Reduction of ventilation heat loss through:
   The waterproof envelope of the building.
   Fresh air supply, in accordance with specific requirements of hygiene DIN 1946 (room ventilation techniques) through a heat recovery system with a thermal efficiency of 85% recovery [24].

The cooling energy requirements of the building are reduced by:

1. The installation of an intelligent outdoor sun protection with Azimut-dependent slat adjustment and the annual shading diagram, which is integrated into the building automation system.
2. The installation of an auto dimmer lighting depends on room light [17].

2.3.2. Minimization of primary energy demand

2.3.2.1. Heating energy. The necessary heat is provided by three thermal production facilities:

1. Three gas/oil burner in the boiler room of the main building, the maximum total heating power is 4560 kW.

2. Heat recovery system of air compressors, the maximum total heating power is approximately 700 kW.
3. Solar thermal power plant with a gross collector area of 1330 m^2 on the roof of the main building, the peak power approximately 1200 kW, the maximum continuous power is approximately 650 kW.

For heat generation, heat recovery and solar thermal device have priority over the heating system, i.e., burners provide heat only when the solar heating and heat recovery are not sufficient to supply all consumers [25].

2.3.2.2. Cooling energy. The cold required in the building is provided by three adsorption cooling machine with a total cooling capacity produced of approximately 1000 kW. For the re-cooling of the cooling machines there are three cooling towers with a maximum cooling capacity installed of approximately 3000 kW. Depending on the outside temperature and the cooling demand, the cooling towers can be used as free-cooling, i.e., the cold of the cooling towers passes directly to consumers. In addition, approximately 380 energy piles supplement with a cooling capacity of about 210 kW directly to the thermal activation of the components. The adsorption cooling machines, according to the characteristics of the system, have a maximum efficiency of 0.6, i.e., the machines require almost twice the heating energy (input energy) to produce cooling energy (output energy). Therefore, the system of adsorption cooling machines is used only when heating from heat recovery and thermal solar energy are sufficiently available. Depending on the amount of thermal energy generated, one, two or three adsorption cooling machines are running. When cold consumers require more cooling energy than produced by the adsorption cooling machines, the difference is taken from the cooling system of the main building. Through this operation, except in special situation, the system ensures that the adsorption cooling machines do not operate with primary energy [25].

2.4. Building automation system

2.4.1. Basic structure

In the Technology Centre a building automation system is installed, based on LonWorks technology (LON). The LON system is decentralized, which means that the operation of the system does not depend on a host computer, but the smart bus components communicate directly with each other. This limits the data traffic on the sections in the bus system and maximizes the reliability of the system. Through the fully standardized communication protocol and defined application profile of the application areas a wider interoperability of the various bus nodes is guaranteed. Considering the physical and logical properties, the system helps to extend or change the network. On the basis of a uniform automation system is carried out a cross-functional integration of all engineering areas of the building such as HVAC, plumbing, electricity, lighting and sun protection [26,27]. A central computer is needed only for the maintenance or modification of the system, for example, the implementation of the new components of the bus or system, as well as for the building management system (BMS) is required. The BMS is at the management level and allows a convenient way to display both, configuration and alarm, and the implementation of higher level functions.

The physical structure of the systems consist essentially of two horizontally separate levels, the LON network (FTT-10-Bus) and a LAN TCP/IP. In the FTT-10-Bus, bus components, such as DDC, actuators, sensors, meters, etc., are connected to the LON network, LAN is the fast backbone for a long distance bridging and transmission of data to BMS computer. At the interfaces between FFT-10-Bus and LAN meets the LAN routes between the two levels. A simplified diagram of functions of the automation system of the building is shown in Fig. 8.

2.4.2. Control functions

The command and control functions are, especially when they are of complex nature, implemented in the free programmable

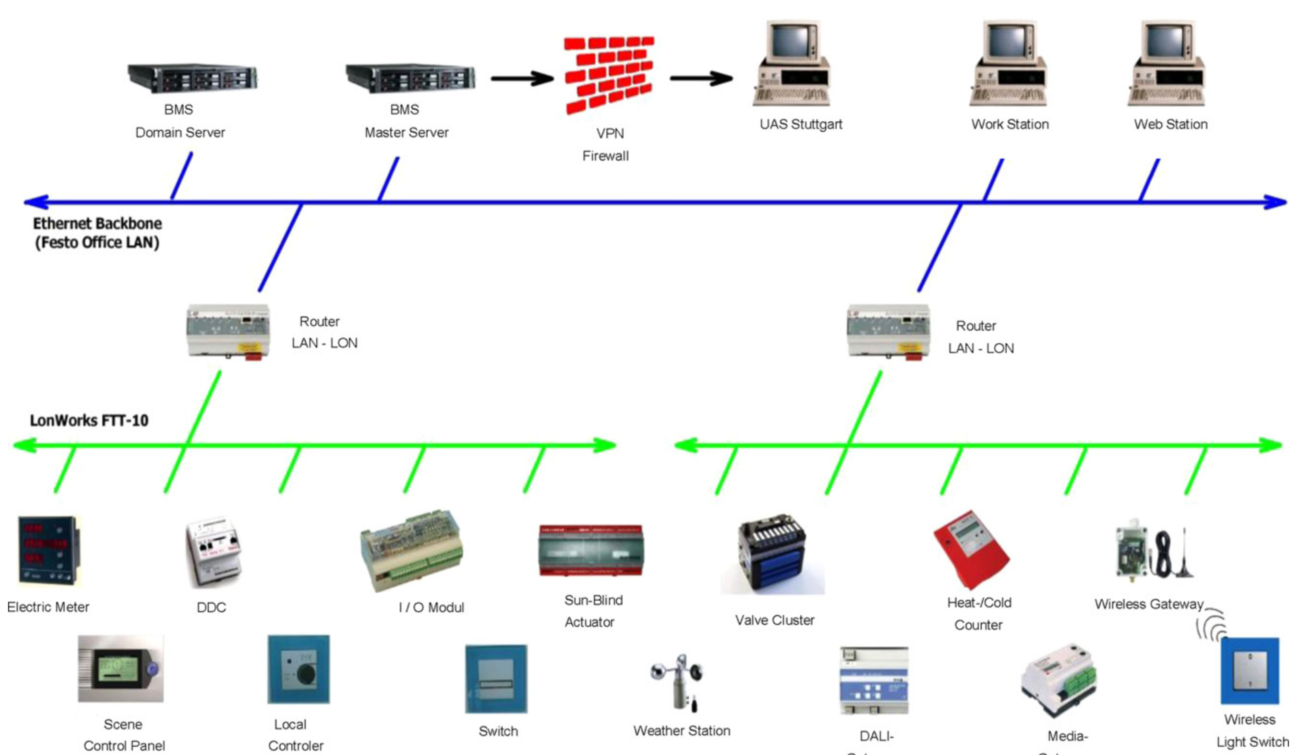

Fig. 8. Schematic diagram of the system of building automation.

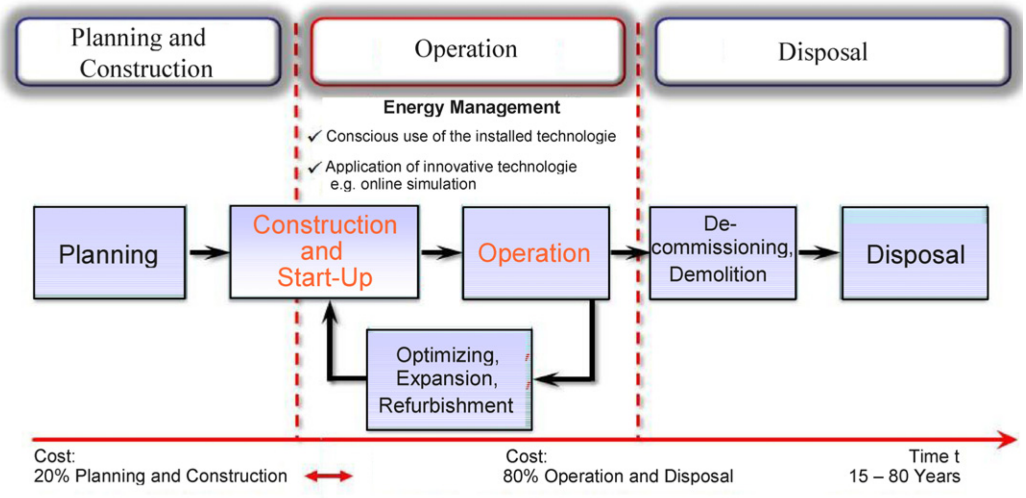

Fig. 9. Life cycle of an industrial and administrative building.

controllers (DDC), are in part firmly stored in the components of the bus. For example, controls of ventilation or heating and cooling systems in the distribution program of the DDC. The system function of sun protection, lighting or the meters of the amount of energy, however, they will be in the form of configurable standard applications, which are supplied by the manufacturer, actuators, sensors, and other bus nodes are loaded into standard applications. In order to put a system to run, all the necessary components are connected to each other through the called variable network. For example, the shutter actuators can work connected to the station of weather condition and time, to get the real values of lighting, wind power and time [18,28].

3. Methods

Buildings demand energy in their life cycle, both directly and indirectly. Directly for their construction, operation (operating energy), rehabilitation and eventually demolition; indirectly through the production of the materials they are made of and the materials technical installations are made of (embodied energy) [29]. With the evaluation of the life cycle of an industrial and administrative building, as shown in Fig. 9, the operation of the building requires a large part of the total building cost. Investments in efficient energy management during the planning phase are amortized quickly and paid off during the total period of the building's life [15,25].

While the development of the components of the building's automation in terms of increased energy efficiency is very advanced, intelligent management of the integrated systems for the optimal interaction of the components is still missing. Simulation systems offer solutions in this context, such as online tools used to monitor the automated system, for the optimized management and also to clearly reduce the necessary time for performance optimization.

3.1. Simulation based control strategy optimization

Simulation models of HVAC systems and rooms, e.g. TRNSYS and INSEL, are very often used during the planning phase of a project for a proper system design, Fig. 10. However, these simulation tools offer additional possibilities for control algorithm development and performance observation which are not used in practice so far. The development of complex control algorithms of systems in the simulation environment (e.g. HVAC) offers the possibility to test and optimize the developed control code for all possible boundary conditions in a very efficient manner [26].

3.2. Simulation based performance observation

For energy efficient operation, especially of larger and complex buildings, a permanent performance observation of the relevant HVAC systems and of the building's overall energy consumption is extremely important. The experience shows, that even systems which have once been analyzed in detail and were optimized can significantly change their operational behavior due to component degradation, system errors and false operation caused by inappropriate maintenance (valves opened and forgotten to be close, blocked water supply, wrong setpoints etc.). Owing to the large number of HVAC systems in larger buildings, errors of single systems are often not detected although they are monitored in the BMS. The main problem is that a short daily look at simple line graphs is often not sufficient for fault detection and time for more detailed analyzes is not affordable. With the support of simulation based performance observation, the effort for a detailed performance analysis is significantly reduced, since a closer look at the performance data is only required for plants with detected errors.

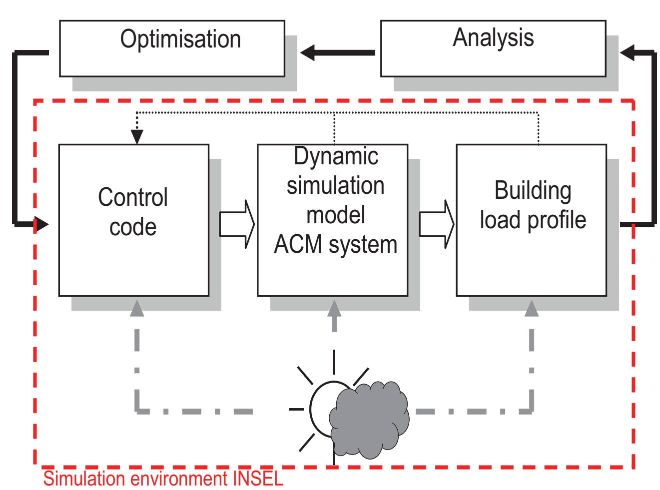

Fig. 10. Principle of simulation based control optimization.

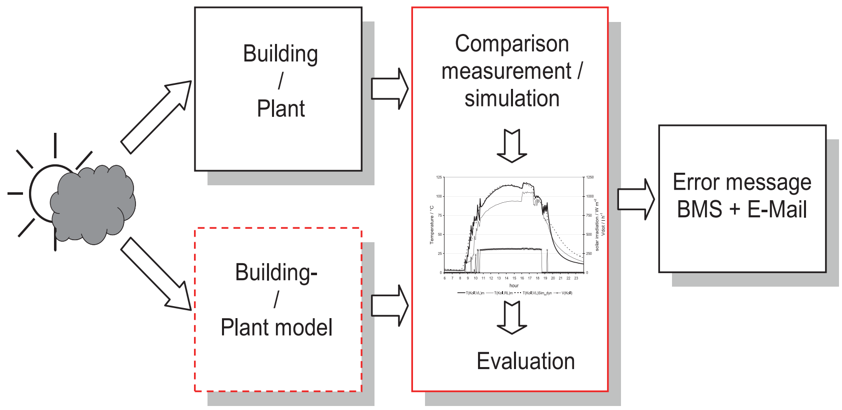

Fig. 11. Principle of simulation based performance observation.

In the best case, the possible error source can also be detected or at least the number of possible error sources can be isolated by the simulation model [26,27]. Fig. 11 demonstrates the application of simulation based performance observation.

3.3. Performance optimization through predictive control

The thermal mass of the building can be used as passive heat or cold storage in order to provide cooling or heating energy during periods with low primary energy effort and to reduce peak loads during periods with lower efficiency of the supply systems [27,28]. A typical application is the utilization of night time ventilation to reduce cooling loads during the following day. In addition to ventilation, other active systems like cooling towers or chillers can also be operated during night time or early morning hours at high COP to precool the rooms and their surrounding construction to a certain temperature level [29]. Many different analyzes have been performed for various building typologies, including large office buildings [30,31]. This significantly reduces the typical peak cooling load during the early afternoon of the following day. However, care has to be taken to avoid the active or passive cooling of rooms during night-time when it is expected that the ambient conditions suddenly change and no cooling energy would be required during afternoon of the following day [32–34]. To avoid such kinds of unsatisfying control, predictive simulation tools can be used which consider the weather prediction from a web service to analyze the most efficient control strategy of the HVAC system for the following days [35–37]. Fig. 12 shows the principles of a predictive control application.

An example for predictive control we can find in the Festo TC, as it is shown in Fig. 13. Comparing different control strategies to control the temperature of the TAC. In finger 2, we find a conventional control on the base of 24 h average of the outside temperature. In finger 4, there is a predictive control that adds the temperature of the weather forecast of the next 24 h to the last 24 h outside temperature average. In Fig. 13 we can see the outside temperature, the average of the last 24 h and the predicted temperature calculated (the last 24 h + the next 24 h). Between the 16th April and the 8th of May 2009 the influence of the forecast value is clearly visible as the outside temperature fluctuations are big. Between the 9th of May and the 20th of May 2009 the influence of the forecast value is not so clearly visible as changes of the outside temperature are small.

The TAC is a relatively slow system to cover the basic heating and cooling loads in the building, the control of the temperature through the calculated forecast value adjusts the power of the TAC early in time to accommodate fluctuating outside temperatures. The result of the predictive control is first a higher comfort as the room temperature fluctuates less, second the reduction of heating or cooling energy for the ventilation systems, which would have to supply the energy difference, third available energy can be used in advance through the use of the thermal mass.

3.4. Data transfer between BMS and simulation tools

For the implementation of online simulation tools, interfaces are required which enable an online data exchange of measured and simulated values between the BMS and the simulation tool. From the experience in other projects this can be a very difficult and time consuming task. In the ideal case the BMS offers an OPC interface for online data exchange. In this case an OPC client of the BMS writes the actual measured values or status information

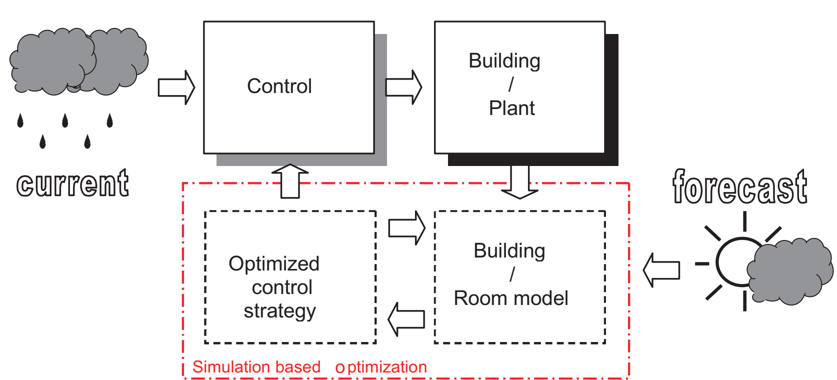

Fig. 12. Principle of simulation based predictive control.

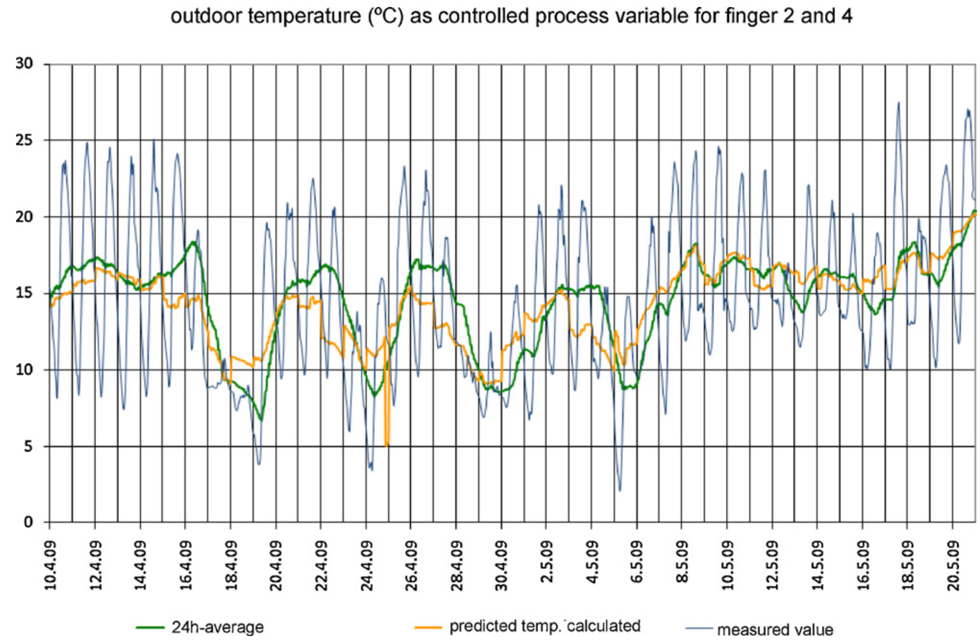

Fig. 13. Measured outdoor temperature and the associated curves of the 24-h average value, and the calculated prediction mean.

etc. to an own or third party OPC server. A second OPC client of the simulation tool connects to the server and reads the required values from the OPC server, performs the simulation, and writes the results (outlet temperatures, energy consumption and error status etc.) back to the OPC server. An OPC reader client of the BMS reads the simulation results from the OPC server and transfers them to virtual data points within the BMS. These virtual data points are stored in the database and can be displayed in trend graphs together with the measured values of the real system. If a TCP/IP connection over the local network exists, the simulation tool can run on a separate PC from the one of the BMS software. Unfortunately, some of the OPC clients and servers are not clearly defined which means that they sometimes talk a kind of different 'accent'. This may cause serious communication problems which are sometimes difficult to solve. Fig. 14 shows a standard connection solution.

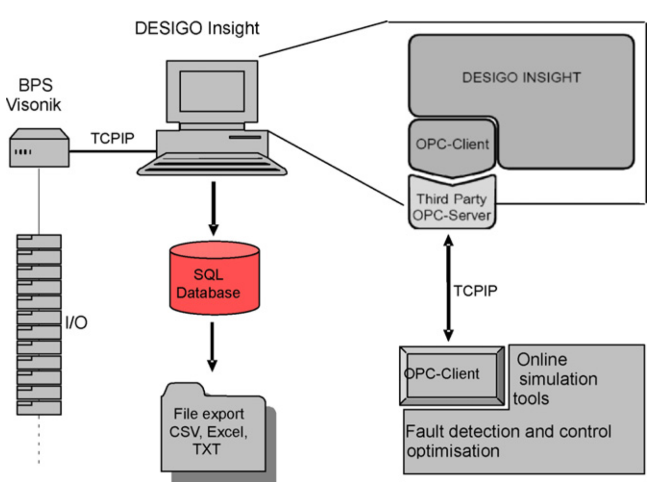

Fig. 14. Simplified data communication structure for online simulations.

4. Detection of some specific errors and solutions: optimization

4.1. Error detection through improved performance visualization methods

Fig. 15 shows carpet plots of the heating and cooling coil of one of the office air handling units installed in the FESTO office building. These air handling units are operated with reduced air flow rate during night time and constant design air flow rate during daytime. As clearly visible from the carpet plots the heating coil supplies heating energy to the supply air during night time and the early morning hours although the ambient temperatures (outside temperature) are not below 16 °C. During daytime the ambient air temperature increases above 27 °C and additional cooling energy needs to be supplied to the rooms. This inefficient behavior was caused by an error in the control of the heating coils. With the help of the carpet plots, such control errors are very fast to detect with only one short glimpse on the graphs. With simple line graphs, as still common in BMS systems, the detection of such an error would have taken much more time or even would have never been detected at all. Altogether, the energy saving potential of the detected error was more than 30% of the heating energy and a not clearly specifiable percentage of the additional cooling energy supplied to the rooms. This clearly demonstrates that for efficient energy management, improved methods of graphical presentation of performance data are essential [14].

4.2. Error detection through simulation based performance observation

The main part of the cooling energy in the FESTO office building is removed by the thermally activated concrete ceilings 'TAC' which are regeneratively cooled by a large number of thermally activated bore piles in the foundation of the building. Due to a significant ground water flow rate, this geothermal cooling system is very efficient. The remaining part of the cooling energy is removed by the ventilation system (1.6 air changes per hour) and

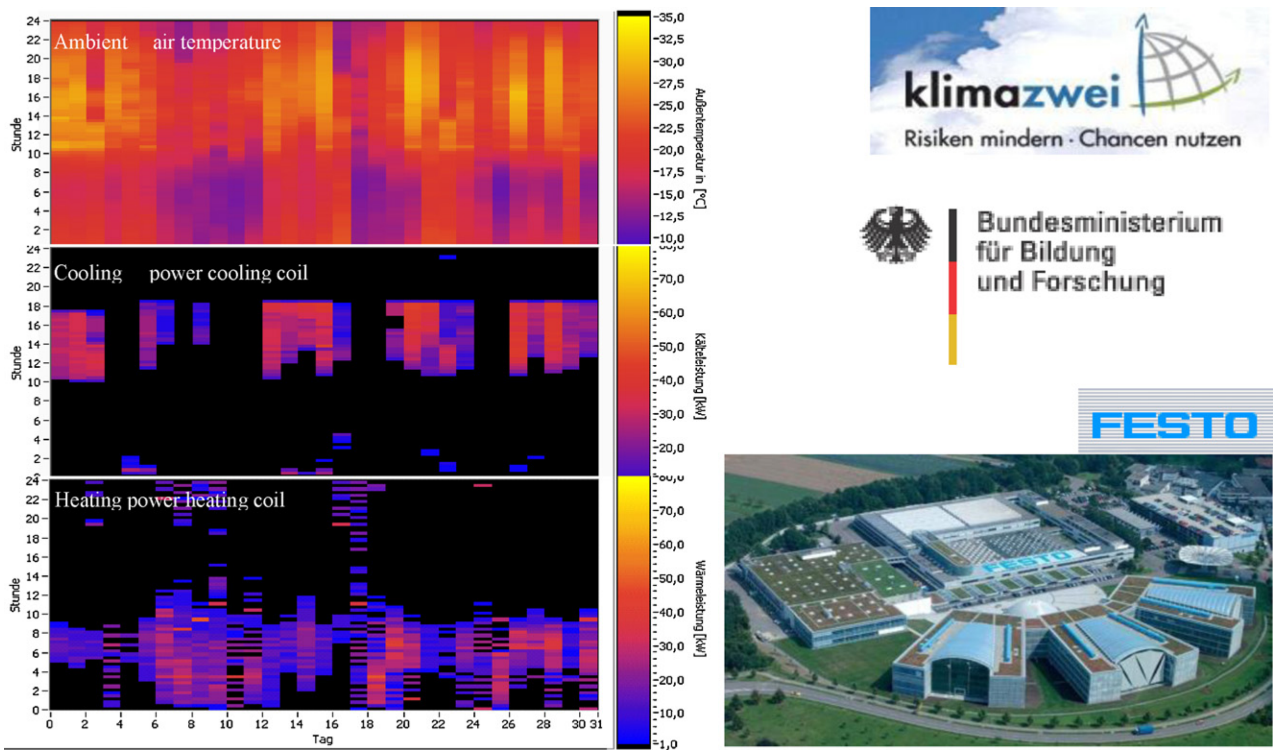

Fig. 15. Carpet plots of the cooling and heating power of one air handling unit in July 2009.

additional cooling coils. For one of the six office fingers shown in Fig. 8, detailed monitoring of the energy flow dynamic simulation model have been developed for each of the 4 floors. These models include the TAC, the ventilation system, the additional cooling/heating coils and the control of the active systems. Comparative online simulations showed a very good agreement between the measured and simulated room temperatures for the ground floor, 1st floor and 2nd floor. For the 3rd floor, shown in Fig. 16, a significant temperature difference of about 2 K lower was calculated by the simulation tool, which was determined to be a system error. Further analyzes showed that if the TAC was turned OFF in the simulation model nearly the same temperatures were predicted as measured in the rooms. In consequence the stopcocks of the thermally activated ceiling in the third floor were checked, with the result that all of the stopcocks were found to be closed and therefore the thermally activated ceiling was not active in this floor at all. In consequence the part of conventional cooling energy was much higher. This example clearly demonstrates the potential of simulation tools for automated fault detection and fault diagnosis. Without the simulation tool the detection and localization of the error would have been much more difficult and time consuming.

4.3. Simulation based control strategy optimization

As already described in the previous chapter, the main cooling load in the FESTO building is removed by thermally activated ceilings which are connected to a regenerative geothermal cooling system. The goal of the implemented control is to remove as

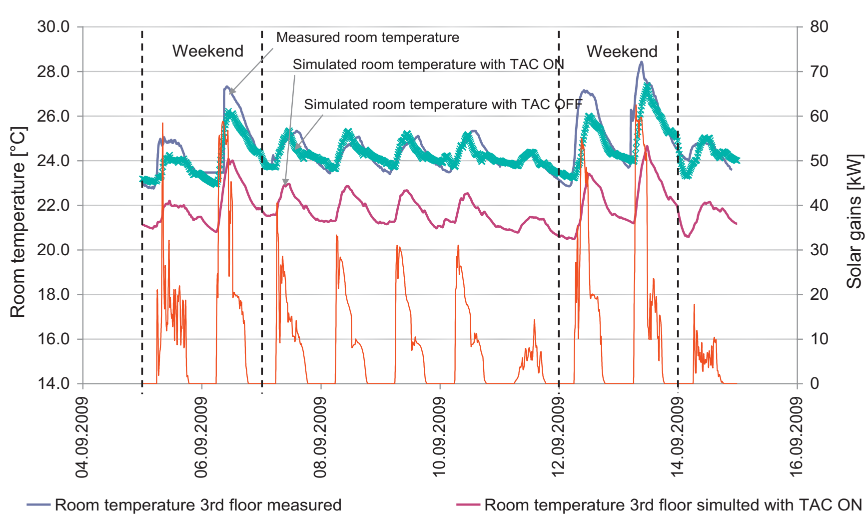

Fig. 16. Measured and simulated room air temperatures for the 3rd floor of one of office finger.

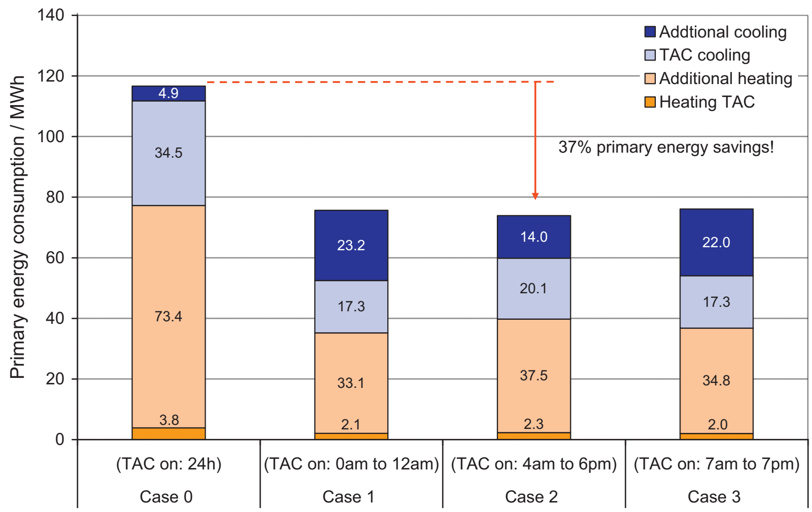

Fig. 17. Primary energy consumption for heating and cooling in one office finger.

much cooling energy as possible by this system. Therefore, in the actual control, the pump of the thermally activated ceilings is permanently in operation. The supply temperature is controlled in dependence on the external temperatures. In winter mode heating energy is supplied to the system by a large 1,218 m^2 solar collector field and, if this is not sufficient, additionally by gas boilers. However, a detailed analysis of the performance data showed a significant heating energy demand during the cooling period, which indicates that due to the permanent operation of the thermally activate ceilings sometimes too much cooling energy is supplied to the rooms. Case 0 in Fig. 17 shows the primary energy consumption for heating and cooling and the actual control strategy for the period from March to end of September 2009 for one of the six office fingers of the FESTO office building in Esslingen. For the cooling energy delivered by the thermally activated ceiling, the primary energy consumption was calculated from the electricity consumption of the pump multiplied by the primary energy factor for electricity (this factor is used to calculate the quantity of primary energy necessary to produce electricity). According to GEMIS [38], a program that is used for the analysis and database of energy systems, materials and transport, a factor of 2.7 can be used for the electricity mixture in Germany, i.e., in order to produce 1 kWh of electricity in Germany 2.7 kW of primary energy are needed. For the additional cooling energy an electrical COP of 3 was considered for the chillers. For the additional heating a gas boiler with a primary energy factor of 1.2 was assumed. With the validated simulation model of the building and the HVAC system the effects of different operation regimes with shorter operation of the pump (12 h or 14 h instead of 24 h) were analyzed. In case 1 the pump of the TAC is in operation from 0 to 12 am, in case 2 from 4 am to 6 pm and in case 3 from 7 am to 7 pm.

As clearly shown in Fig. 10, the reduced operation time of the TAC significantly reduces the overall primary energy consumption by 37% in the best case. The reason for this is that the primary energy consumption for heating is reduced by more than 50% and the primary energy consumption of the TAC (only caused by the pump) is reduced by 50% in case 1 and 3 and by 42% in case 2. The required additional cooling energy demand increases due to the shorter operation time of the TAC by a factor of nearly 5 in case 1 and 3 and by a factor of 3 in case 2. This demonstrates that with a simple reduction of the operation time of the TAC, a significant reduction of the primary energy consumption of more than 35% is reached. However, there is still an optimization potential of 10% to 20% if the TAC operation time would be controlled dynamically using weather forecast data together with a simulation based predictive control optimization tool as described in point 2.

5. Conclusions

The simulation based control optimization methods includes control strategy development, test within the simulation environment and simulation based performance observation with automated error detection through predictive control optimizations using simulation tools together with weather forecast data. As described and demonstrated, these tools allow a very efficient error detection of false installations and slow degradations as well as errors caused by inappropriate maintenance. Furthermore, simulation based predictive control offers the opportunity of a better utilization of the buildings and their thermal mass. This helps to equalize peak loads in the early afternoon and to operate the active cooling systems more efficiently at higher power e.g. during the early morning hours. The expected optimization potential of the described tools is in the region of 10–30% or more of the actual energy consumption of the buildings, this percentage is variable depending on building characteristics and the management strategies.

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