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# Energy Efficient Operation of Existing Buildings Through Simulation Based Control Optimisation

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## Abstract

Energy management in existing older buildings in most cases is still a simple collection of energy consumption data for heating, cooling and electricity on a monthly or annual basis. However, this backward looking method allows the detection of too high energy consumptions only after a quite long time period and offers limited possibilities for fault detection. For more dynamic energy management energy meters are often connected to the existing building management systems (BMS). However, these systems often offer limited possibilities for graphical performance analysis and visualisation.

Current research projects within the German funding program for the construction of energy optimized buildings (EnOB) and the subprogram for energy optimized building operation (EnBop) focus on the development of improved graphical representation methods and methods for the generation of reference values for heating and cooling energy consumption and plant observation. In a current research project called ‘EnSim’, zafh.net focuses on the energy efficient operation of existing older buildings through simulation based control observation and optimization. The project is funded within the EnBop program of the German Ministry for Economy and Technology ‘BMWI’ and the demonstration partners are the Robert Bosch GmbH with their real estate in Schwieberdingen and the Südwestrundfunk (SWR) with their real estates in Stuttgart and Mannheim.

In the paper the EnSim project is introduced with the main research tasks and application goals to be reached and the demonstration project partners involved. In the second part different methods used for simulation based fault detection and control optimisation will be introduced and demonstrated on first application results.

## 1. Introduction

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. A 60 building case study of Lawrence Berkeley National Laboratories in commercial buildings for example showed that 50% of the buildings had control problems. Analysing the savings through operation and maintenance in 132 further buildings demonstrated that 77% of the savings were obtained by correcting control problems (Claridge et al., 1994). Energy savings in such buildings are usually in the range of 10-25%, sometimes as high as 44% (Hicks et al, 2000). This demonstrates the need of a detailed performance observation in buildings. However, energy management in the building sector is 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 reduce the influence of varying weather conditions and to allow a better comparison of the heating energy consumption of different years. For electricity consumption and cooling energy consumption such a simple kind of normalization method does not exist. Furthermore, this backward looking method only allows the detection of too high energy consumptions after a quite long time period and the reasons for an increase in energy consumption is very difficult or nearly impossible to detect.

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For a more dynamic energy management during the last 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 then locally controls the mixture of heating and cooling to achieve the desired room temperature. A secondary function sometimes is to monitor the level of human-generated $CO_2$, mixing in outside air with waste air to increase the amount of oxygen while also minimizing heat/cooling losses. Systems linked to a BMS typically represent 40% of a building's energy usage; if lighting is included, this number approaches 70%. BMS systems are therefore a critical component to managing energy demand. Improperly configured BMS systems with control errors can easily increase the energy consumption of buildings in the region between 5% and 30 % in some cases even more (Fisch, N., 2008; Neumann, C. 2008).

One of 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 system is still difficult and in some cases nearly impossible. Current research projects e.g. within the German funding program of the Ministry for Economy and Technology 'BMWI' for the construction of energy optimized buildings (EnOB) and the subprogram energy optimized building operation (EnBop) therefore focus on the development of methods for improved graphical representation, methods for generating reference values for heating and cooling energy consumptions by simulations (Schmidt, F., 2008; Burhenne, S., 2008) and the statistical evaluation of measured consumption data (Neumann, C. 2008).

For automated online fault detection and diagnosis (FDD) and model based control of energy plants and building components simulation models can be used. Simple control systems for radiators in test room configurations have been analyzed online using the building simulation tool ESP-r without yet a commercial BMS (Clarke et al., 2001 and 2002) and experiments have been carried out for model based control of e.g. heat exchangers and humidifiers in air conditioning systems in car painting processes (Uchihara et al., 2002).

For the implementation of an active and complete energy management system often a large number of new sensors and energy meters are required need to be connected to the local BMS. The costs for the connection and implementations of new data points for sensors are in the region of 400 € to 800 € per sensor and between 1.500 and 2.000 € per heating or cooling energy meter. The costs for the heating and cooling energy meters are higher since typically four or more datapoints are required to monitor the supply and return temperatures, the mass flow rate and the energy consumption. The costs for the installation of heating and cooling energy meters strongly dempends on the installation situation and the tube cross section. Therefore, the costs for heating or cooling energy meters vary between 1.000 € and 2.500 €. Additional electricity meters are typically much cheaper especially if no officially calibrated meters are required. This often the case if they are only used for energy management purpose and not for billing. The prices for not officially calibrated meters varies depending on size between 150 € and 800 € including installation. According to Schmidt, F. 2008, the total costs for the implementation of an energy management system should not increase above 10 - 20% of the annual energy costs of the building to be still economically feasible. Therefore, the installation of energy meters should be limited to the minimum number required for an efficient energy management. For a quite big number of systems with e.g. constant mass flows it is sufficient to calculate the energy consumption from the existing sensors and the known or manually measured energy consumption of the components.

In the following paragraphs the project EnSim 'Energy efficient building operation through simulation based control' is introduced. Despite of the project partners with their building stock and building management systems the simulation based methodologies used and data transfer solutions found within the project are introduced and described in detail. In the last part of the paper applications and results of simulation based observation and control optimisation are demonstrated.

## 2. EnSim 'Energy Efficient Building Operation Through Simulation Based Control'

Within the research project called 'EnSim', zafh.net focuses on the energy efficient operation of existing older buildings through simulation based control observation and optimisation. Furthermore, in some buildings the energy distribution infra structure is analysed, the hydraulic is optimised and inefficient components like old over dimensioned pumps or fans are replaced by innovative, highly efficient components. To evaluate the effect of the different measures on the energy consumption the situation before and after their application is monitored and analysed in detail. The project is funded within the 'EnBop' program of Ministry for Economy and Technology 'BMWI' mentioned above.

The demonstration partners within 'EnSim' are the Robert Bosch GmbH with their real estate in Schwieberdingen and the Südwestrundfunk (SWR) with their real estates in Stuttgart and Mannheim. Figure 1 shows some photos of the real estates and buildings of the two demonstration partners.

The official project start of EnSim was on 1st of February 2009 and the project duration is 3 years.

**Figure 1: Demonstration Projects within EnSim**


### 2.2 Description of the Real Estate of the Robert Bosch GmbH in Schwieberdingen

The building stock of the real estate of the Robert Bosch GmbH in Schwieberdingen comprises a floor area of about 150.000 m² which is used for offices and laboratories. The whole real estate is equipped with an elder grown Siemens building management system, which is operated and maintained by DMS. At project start of EnSim only very view energy meters were installed, which were mainly used for billing purpose and not connected to the BMS. The installed system furthermore offered only very few possibilities for performance visualisation in form of simple line graphs and a very cumbersome handling of measured performance data for external analysis. Within the EnSim Project only some of the buildings are analysed in detail.

Building Si 101 (see Figure 1) has been completely refurbished a few years ago with heat insulation measures on the opaque part of the façade and on the roof. The windows were built as double façade with double glazed windows on the room facing side. In this building control optimisation potentials are analyzed for the existing induction cooling / heating system. Despite of the energy efficiency also an optimised thermal comfort shall be reached. In the buildings Si 501 and Si 205-207 innovative control strategies for the reduction of the air flow rates of the installed air handling units will be applied and analyzed in detail. However, the main focus within EnSim will be on the buildings Si 205-207 which are of exactly the same shape and with similar utilisation but with different insulation standards. Si 205 has been refurbished in 2008 with heat insulation measures on the façade according to the national standard and Si 206 will be refurbished within the EnSim project to a much higher thermal standard. The goal of the planned refurbishment measures is to reach an energy consumption which is at least 30% below the national regulations. Si 207 will be used as reference building for the original thermal standard and therefore remains in the original status. This comfortable situation offers the possibility for a detailed analysis of the efficiency of different insulation measures. Since the HVAC system wasn't changed in Si 205 it furthermore offers the opportunity to analyse how the HVAC system needs to be adapted to the new thermal standard to meet both the required thermal comfort conditions and an energy efficient operation. For the performance analysis of the buildings Si 205 to 207 a measurement concept has been developed within EnSim. The required additional sensors and energy meters are now in place and connected to the BMS. First data collection started in February 2009.

### 2.2 Description of the Real Estate of the SWR in Stuttgart

The building stock of the SWR in Stuttgart comprises a total building volume of 223.000 m³ with 47.000 m² heated floor area. All the buildings were mainly built around 1970 with typically low thermal standard. Figure 2 gives a more detailed impression of the analysed buildings, its utilisation and the installed HVAC systems. The buildings were refurbished during the years 1997 and 1998. Since the buildings are under historical preservation protection only on some facades heat insulation measures could be applied. Therefore, manly the glazing of the windows was exchanged. Additionally some heat isolation measures were applied on the inside of some of the external building walls. In the year 2002 efficiency measures were applied to the HVAC systems by AXIMA within an energy contracting model. These measures mainly focused on the larger ventilation systems where frequency inverters were applied for air volume flow control, heat recovery systems were implemented and inefficient ventilators were exchanged. These measures reduced the heating energy consumption of the building by more than 30% and the electricity consumption by more than 20%. Actual the annual heating energy consumption of the buildings is 165 kWh per square meter heated floor area and year. The cooling energy demand was so far not measured separately. Since compression chillers are used the cooling demand is included in the total electricity consumption of 144 kWh per square meter heated floor area and year. The high electricity consumption is despite of the HVAC systems and the office equipment mainly caused by the radio and TV sending technology and the technology used in the different studios.

The whole building complex is equipped with an existing over the years grown Siemens V2 building management system with 71 process units and 10.200 datapoints. All together, 69 different air handling units supply fresh and treated air to a large number of different radio and TV studios and office spaces. At project start only a few number of energy meters were installed and connected to the BMS. Within EnSim a clear monitoring concept including all energy flows has been developed for the whole building complex and for different building parts and HVAC systems analyzed within EnSim. Four floors of one of the office buildings will be equipped with energy meters to measure all energy flows (heating, cooling, lighting and equipment) separately for each floor. Here the effect of different control strategies of the HVAC, shading and illumination system on the energy consumption will be analysed. Furthermore, simulation tools for the prediction of the cooling and heating energy demand for automated performance observation and innovative predictive control strategies will be tested here in detail. The installation and connection work of the additional energy meters and sensors is still in progress. The main problem for an efficient energy management was that the installed elderly BMS system offers only very limited possibilities for performance data visualization (simple line graphs, cumbersome data transfer for external analyses) which makes the energy management at present very time consuming and expensive. Therefore, no detailed energy management was implemented at project start of EnSim.

**Figure 2: Building view, TV studio and HVAC systems of the SWR buildings in Stuttgart**

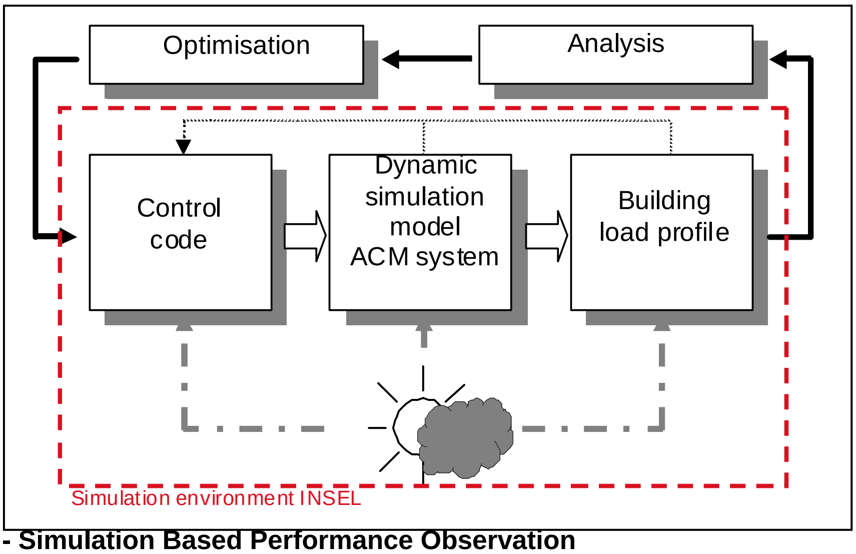
### 2.2 Main Objectives and Methodologies Used

The main focus of EnSim is to demonstrate the effect and potential of a more active energy management system which is supported by simulation tools for automated performance observation of the heating and cooling energy demand of the building and of the relevant HVAC systems. As the most integrated stage in the project it is planned to test simulation based predictive control strategies for a better utilisation of the buildings thermal mass for one selected building part of the SWR. Within EnSim simulation tools are used in three different levels of integration as described below.

**- Simulation Based Control Strategy Optimization**

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 praxis so far. The development of complex control algorithms of e.g. HVAC systems in the simulation environment offers the possibility to test and optimize the developed control code for all possible boundary conditions in a very efficient manner. In EnSim the control strategies of different existing complex HVAC systems are analyzed and optimized within the simulation environment. Figure 3 visualizes this optimization procedure.

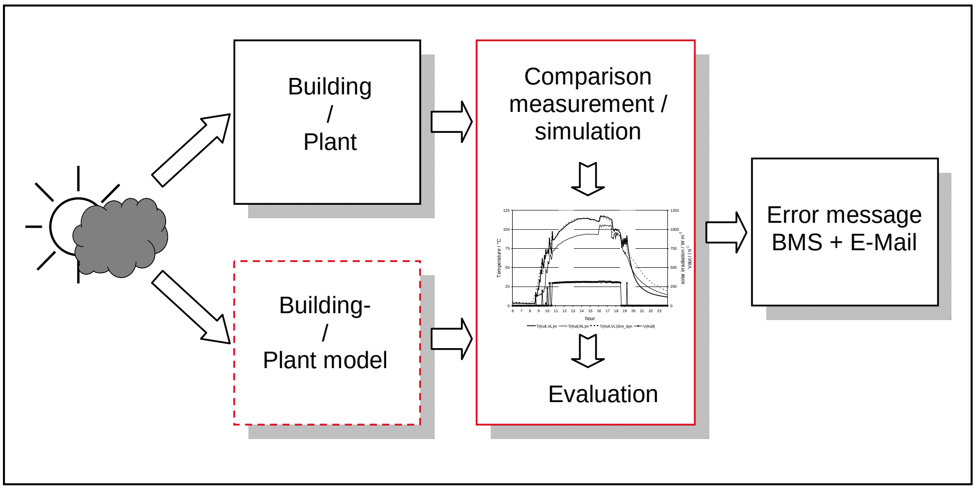
**Figure 3: Prinziple of Simulation Based Control Optimization**




**- 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 buildings overall energy consumption is extremely important. The experience shows, that even systems which once have been analyzed in detail and were optimized can significantly change their operation behavior due to component degradation, system errors and false operation caused by inappropriate maintenance (valves opened and forgotten to close, blocked water supply, wrong setpoints etc.). Due to the large number of HVAC system in larger buildings, errors of single systems are often not detected although they're monitored in the BMS. The main problem is that a short daily look on simple line graphs is often not sufficient for fault detection and time for more detailed analyses is not affordable. With the support of simulation base performance observation, the effort for a detailed performance analysis is significantly reduced, since a closer look on the performance data is only required for plants with detected errors. In the best case also the possible error source can detected or at least the number of possible error sources can be isolated by the simulation model. Figure 4 demonstrates the application of simulation based performance observation:

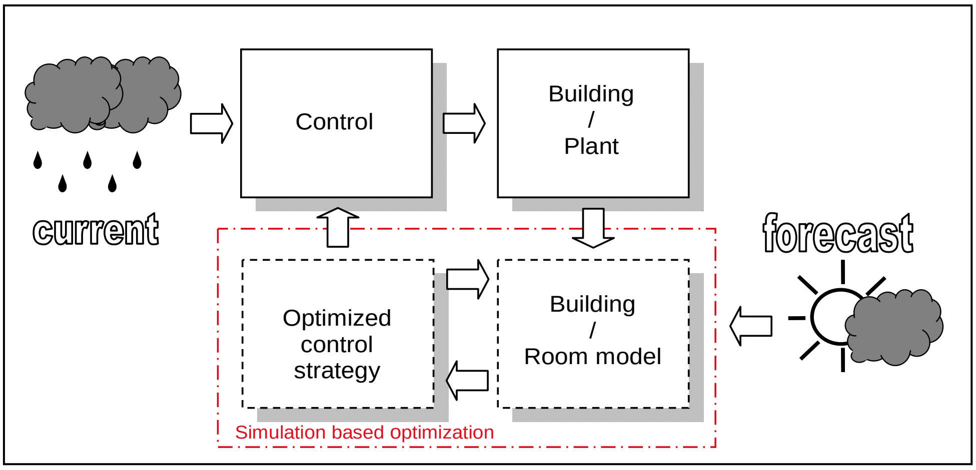
**Figure 4: Principle of Simulation Based Performance Observation**




**- Performance Optimization Through Predictive Control**

The thermal mass of the buildings offers the possibility to 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. A typical application is the utilization of night time ventilation to reduce cooling loads during the following day. Despite of ventilation also other active systems like cooling towers or chillers can be operated during night time or early morning hours at high COP to precool the rooms and its surrounding construction to a certain temperature level. 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 nighttime when it is expected, that the ambient conditions suddenly change and no cooling energy would be required during afternoon of the following day. To avoid such kind 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. Figure 5 shows the principles of a predictive control application:

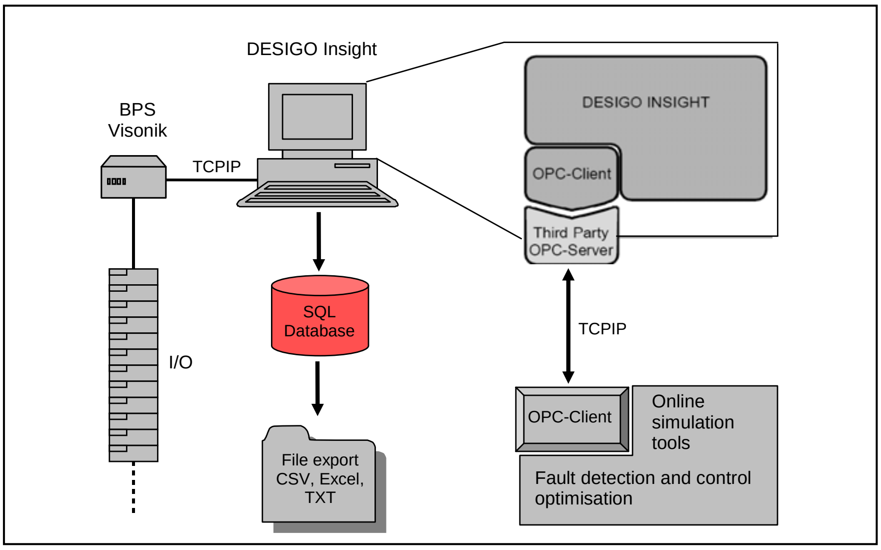
**Figure 5: Principle of Simulation Based Predictive Control**




**- Data Transfer Between BMS and Simulation Tools**

For the implementation of online simulation tools interfaces are required, which enable a 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 system 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 etc. to an own or third party OPC server. A second OPC client of the simulation tool connects to the server an 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 datapoints 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 e.g. over the local network exists, the simulation tool can run on a different PC than the BMS software does. 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. Figure 6 shows the communication solution found for the SWR project which is equipped with a Siemens V2 BMS and a Siemens DESIGO control software, which offers an OPC client for external data exchange. Historical data is stored in a large central SQL database which is located in the SWR computing center.

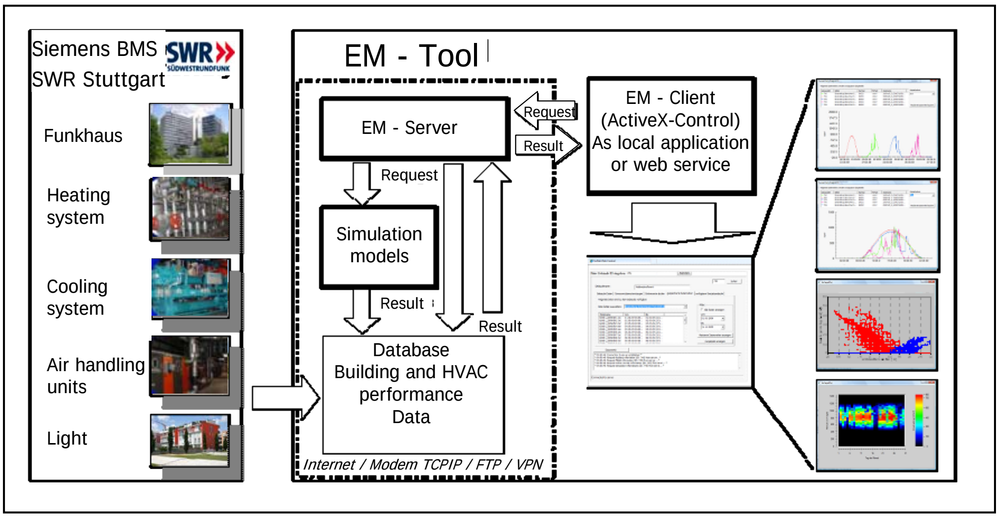
**Figure 5: Simplified Data Communication Structure for Online Simulations**




**- Energy Management Tool**

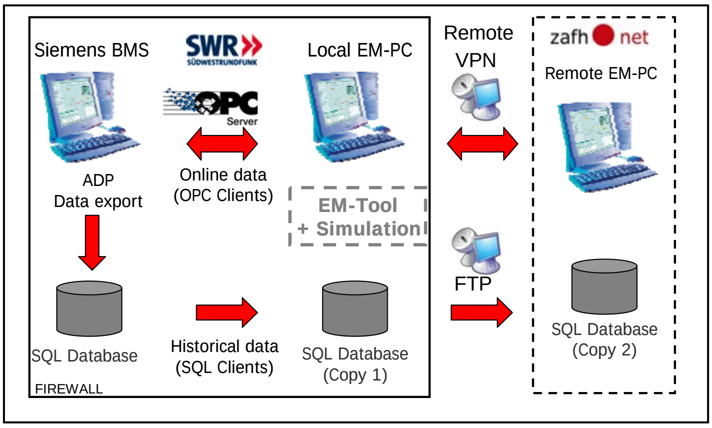
An energy management tool called ‘EM-Tool’ which has been developed at zafh.net within former projects and is used and further developed within the EnSim project. The EM-Tool is designed as ad-on tool with communication interfaces to different BMS systems using OPC, SQL or FTP clients. Additionally, the tool is able to collect data from BMS independent data collection systems which operate as data loggers with communication interfaces either via TCPIP (internet or local network) or modem connection. The architecture of the developed EM-Tool tool is shown in Figure 6. This tool is designed with a client server structure where the server is responsible for the data collection from the different sources and writes this data in a common database. EM-Tool clients are able to connect to the EM-Tool server by TCPIP using the local network or an internet connection. Within the EM-Tool client the user is able to select different datapoints which shall be displayed in a graph for a defined time period.

**Figure 6: Architecture of the Developed EM-Tool**




The selected datapoints and time periods are sent as request to the EM-Server which reads the requested data from the Database or directly from the data source and sends the whole package back to the EM-Client where the results are displayed in the selected graph. For a comfortable fast fault detection different types of graphs are available like simple line graphs, scatter plots and carpet plots. It is also possible to define a number of typical graphs for different HVAC system or building parts which for example plots the room temperature, heating energy, cooling energy, electricity consumption and the On/Off signal of the system in separate carpet plots. This allows quite fast and comfortable fault detections for a large number of systems. Within EnSim the EM-Tool will be coupled with the simulation environment INSEL. With this connection it will be possible to perform different predefined numerical and statistical analyses or even complete system simulations either on request or automatically. The communication structure of the developed EM-Tool is shown in Figure 7.

**Figure 7: Communication Structure of the EM-Tool used at SWR**



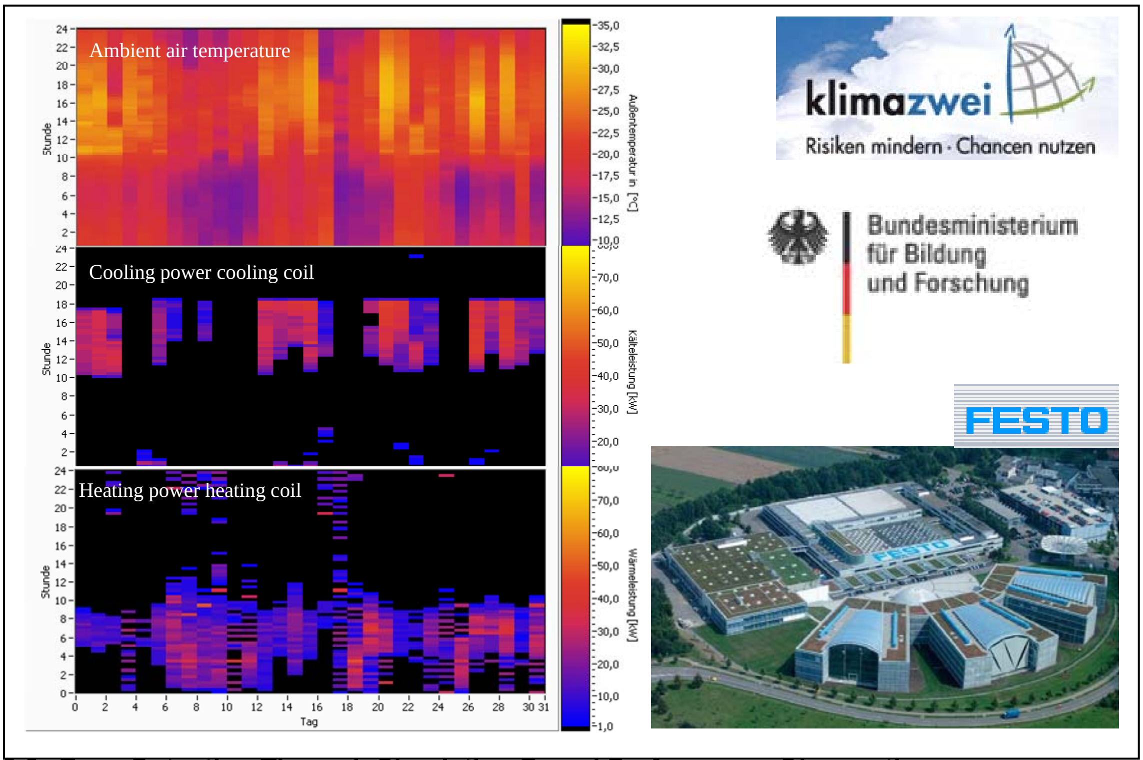

## 3. Application Examples for Simulation Based Observation and Control Optimizations

The current status of the EnSim project is that the monitoring procedure and the implementation of the EM-Tool are clearly defined and some of the additional sensors and meters are already in place others are being installed at the moment. Therefore, up to now only limited monitoring results of EnSim are available which are not sufficient to demonstrate the performance of the simulation based performance observation and control optimisation. However, some of the simulation based techniques have been already tested within a pervious project funded within the BMBF program klimazwei. Within this project two innovative office buildings (FESTO AG & Co. KG in Esslingen and Elektror Airsystems GmbH in Ostfildern) with thermally activated concrete ceilings where analysed for improved control strategies to reduce the summer cooling energy demand. Some of the results are presented as demonstration examples in the following two paragraphs.

### 3.1 Error detection through improved performance visualization methods

Figure 8 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 form 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 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 error 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 been never 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 an efficient energy management improved graphical presentation methods of performance data are essential.

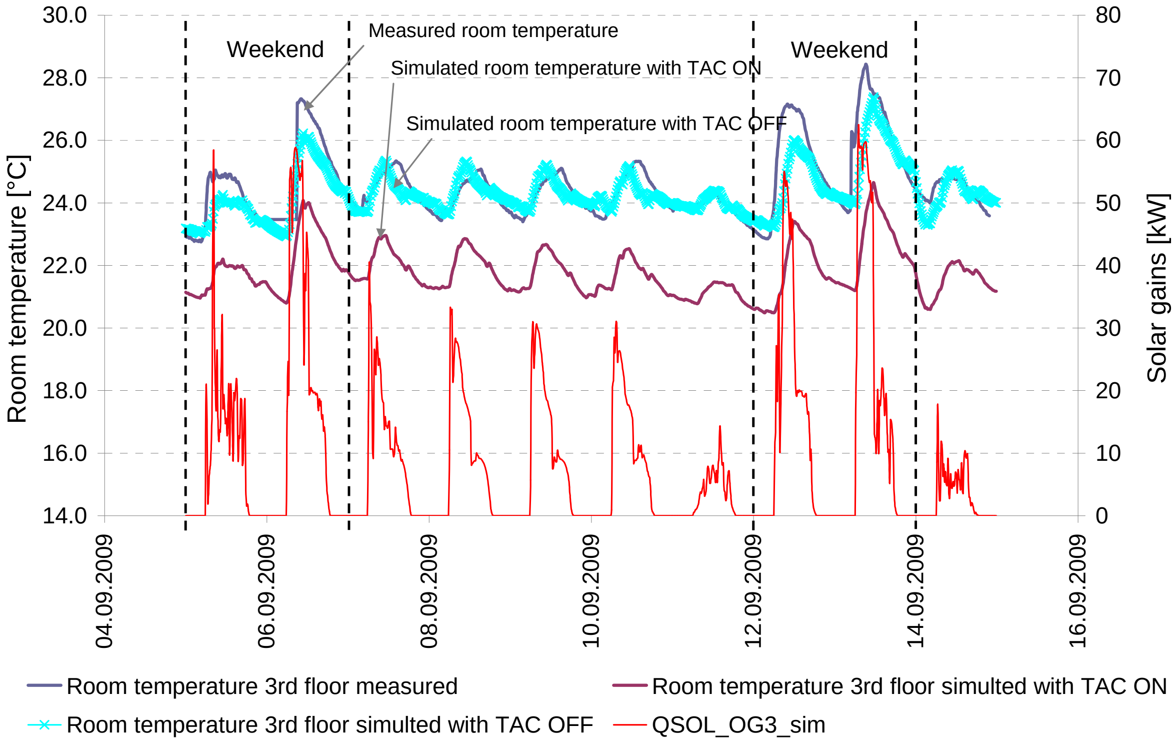
**Figure 8: Carpet Plots of the Cooling and Heating Power of One Air Handling Unit in July**




### 3.2 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 regenerative cooled by a large number of thermally activated bore piles of the buildings foundation. 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 additional cooling coils. For one of the six office fingers shown in Figure 8 with detailed monitoring of the energy flows 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, 1$^{st}$ floor and 2$^{nd}$ floor. For the 3$^{rd}$ floor significant lower temperatures (~2 K) were calculated by the simulation tool which was detected as system error. Further analyses showed, that if the TAC was turned OFF in the simulation model nearly exact 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 closed and therefore the thermally activated ceiling wasn't 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 simulation tool the detection and localization of the error found, would have been much more difficult and time consuming.

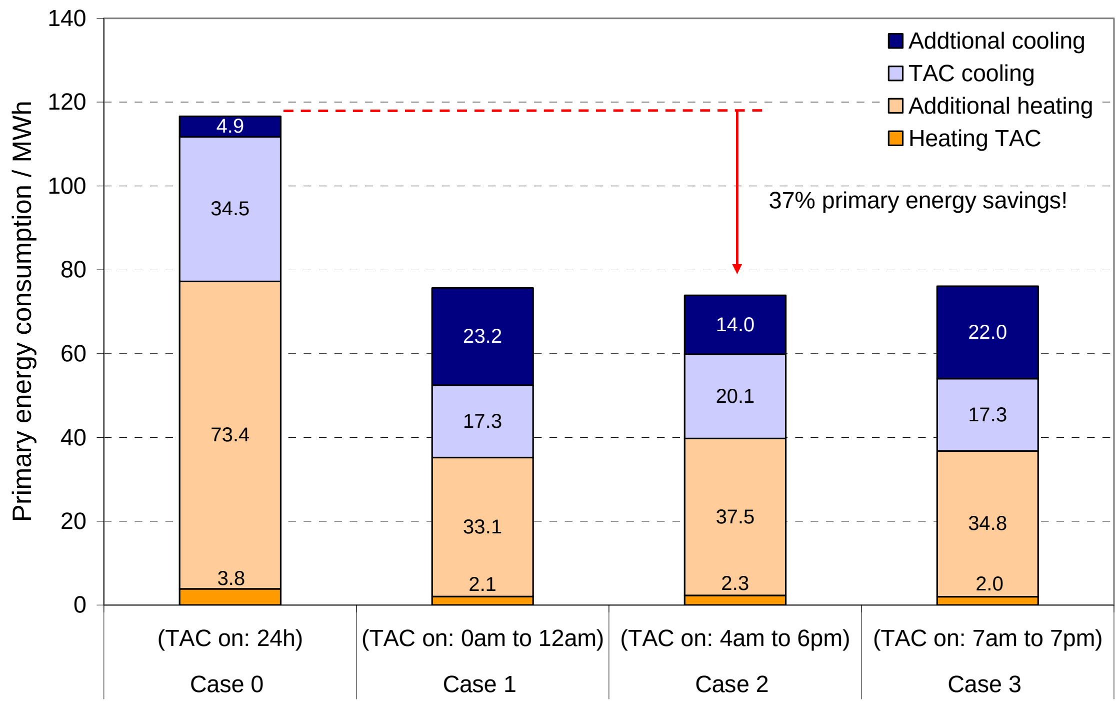
**Figure 9: Measured and Simulated Room Air Temperatures for the 3$^{rd}$ floor of one office finger**




### 3.3 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. Therefore, the goal of the implemented control is to remove as much cooling energy as possible by this system. Therefore, in the actual control the pump of the thermally activated ceilings is permanent in operation. The supply temperature is controlled in dependence of the external temperatures. In winter mode heating energy is supplied to the system by a large 1 218 m² solar collector field and if this is not sufficient additionally by gas boilers. However, a detailed analysis of the performance data resulted in 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 Figure 9 shows the primary energy consumption for heating and cooling of the actual control strategy for the period from March to end of September 2009 for one of the sixe 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. According to GEMIS a factor of 2.7 can be used for the electricity mixture in Germany. 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 effect of different operation regimes with shorter operation of the (12 hours or 14 hours instead of 24 hours) were analyzed. In case 1 the pump of the TAC is in operation from 0 to 12am, in case 2 from 4am to 6pm and in case 3 from 7am to 7pm.

**Figure 10: Primary Energy Consumption for Heating and Cooling in One Office Finger**




As clearly visible from Figure 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 already 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 chapter 2. Such a predictive control optimization tool will be developed and tested within the EnSim Project for one typical office floor of the SWR real estate in Stuttgart.  In this building no thermally activated ceiling is available, but the thermal mass of the quite heavily constructed building still offers a significant storage capacity which van be used for a primary energy optimized control.

## 4. Conclusions

In the present paper the new research project EnSim ‘Energy efficient building operation through simulation based control’ has been introduced. Within EnSim innovative simulation based control optimization methods are developed and will be tested on buildings or building parts of the cooperation partners SWR Stuttgart and Robert Bosch GmbH Schwieberdingen. The simulation based control optimization methods reach from control strategy development and test within the simulation environment, simulation based performance observation with automated error detection to predictive control optimizations using simulation tools together with weather forecast data.
As described and partly demonstrated, these tools allow a very efficient error detection of false installations, slow degradations and 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% to 30% or more of the actual energy consumption of the buildings.

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