# Modeling a Building Energy System for Development of Energy Efficient Systems of Shopping Centers

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## Abstract

In the last years, the global shopping center (SC) inventory increased significantly. Additionally, the energy demand of SC is in general high compared to other commercial buildings. Thus, research in the field of energy efficient SC is becoming increasingly important.

In this paper, an approach for modeling the building energy system (BES) of SC in Modelica is presented. The energy saving potential in the overall system of a recently proposed ventilation concept for SC is investigated (Mathis et al., 2015). Therefore, following the presented approach, three different supply system variants are modeled. The simulation results show that the annual primary energy demand for air conditioning can potentially be reduced by up to 35.1 %.

## Introduction

Research in the field of energy efficient supply of shopping centers (SC) is becoming increasingly important because their number is growing throughout Europe, as well as the Americas and Asia. In the first half of 2015, the total gross leased area (GLA) in Europe amounted to 152.6 million $m^2$ with an annual increase of 3.3 % (Cushman & Wakefield LLP, 2015). Between 2012 and 2014 in the Americas, 1006 new SC have been developed, 350 in Europe and 303 in Asia, amounting to a total of 46,846 SC in the regions combined (Cushman & Wakefield Inc., 2014). The growth of the total GLA in these three major regions combined amounted to 63.9 million $m^2$.

The specific energy consumption of SC is high compared to other commercial buildings. Exemplary, European SC currently consume on the average 290 $\frac{kWh}{a \cdot m^2_{GLA}}$ (Raphael and Agne, 2014). The intense lighting inside showrooms, product presentations of electrical devices, customers themselves and external loads like solar radiation lead to high cooling loads of up to 200 $\frac{W}{m^2}$ (The Association of German Engineers, 2000). Even in the mild climate of Central Europe, cooling loads appear throughout the year. The conventional approach of removing the heat in SC is using all-air systems. To remove a specific cooling load of 100 $\frac{W}{m^2}$ with an all-air system, a specific volume flow rate of about 30 $\frac{m^3}{m^2 \cdot h}$ is required. Additionally, circulating air-cooling units (ACUs) are often installed as a supplementary system. As cooling generators, electrically driven chillers are used in conventional energy supply systems of SC (Falk, 2009)). For covering the heat demand, district heating or boilers are used. The electricity supply is provided by a medium-voltage connection. The main energy consumers in such building energy systems (BES) are the heating, ventilation and air-conditioning (HVAC) systems and the lighting. In the literature, the share of energy consumption of lighting is indicated with up to 50 % (Schönberger et al., 2013) and the share of the HVAC system can be as high as 60 % (Canbay et al., 2004). The typical inefficiencies in case of lighting are mostly due to poor usage of daylight and inefficient light sources, as well as lighting solutions (Woods et al., 2015). The main HVAC related inefficiencies originate from incorrectly selected or inefficient energy supply systems, no scheduling, inefficient control strategies, missing insulation of pipes and missing energy recovery ventilators.

In previous studies, the energy demand of SC were simulated in order to tackle various inefficiencies of these BES. Gentile (2014) and da Graça et al. (2012) analyzed naturally ventilated SC focusing the thermal comfort and energy consumption by using the software tools EnergyPlus and TRANSYS. Kovac and Kovacova (2015) and Stensson et al. (2009) investigated the influence of lighting power in shops, respectively the shading of solar radiation, on the energy performance of a SC. For quantification of the energy demand and the effect of carbon saving measures of grocery stores Jenkins (2008) and Suzuki et al. (2011) investigated existing grocery stores, using the software tool ESP-r. The accuracy of the listed software tool is in general high, but the paramerization and simulation are time consuming (Li and Wen, 2014).

This paper presents an approach for modeling a SC-BES in Modelica for the dynamic system simulation. This approach provides the opportunity for a very fast and accurate enough prediction of the annual energy demand. For parametrization of the SC-BES model planning documentation of an existing SC was used. The simulated monthly and annual demand of cooling and heating energy is compared to the monitoring data of the year 2015 of the considered SC. Mathis et al. (2015) presented in a multi-disciplinary study a promising approach to tackle the inefficiencies of HVAC systems in SC by elevating the cold water supply temperatures and reducing the air change rates Mathis et al. (2015). As a case study, the saving potentials of this new ventilation concept for SC in the overall system will be investigated in this paper. Therefore, following the presented approach, three different supply system variants are modeled. For system comparison, the primary energy demand for air conditioning is determined by annual simulations.

## Characteristics of the considered shopping center

The considered SC was built in 2008 and is situated in Munich, southern Germany. It shows a typical mall structure with tenant placements on the right and on the left of the centrally placed mall. The usage of the considered SC is conventional, without special facilities such as cinemas, hotels or dwellings. With regard to the geometry, the shape of the building is considered to be compact. Table 1 shows an overview of different floor area types, which are spread over six floors. The three upper floors are parking decks and bottom floor is a basement.

*Tabelle 1: Floor areas of the considered SC*

| | Area in m$^2$ |
|---|---|
| Gross floor area | 63,860 |
| Net floor area | 59,326 |
| Mall | 3,724 |
| Rental area | 21,980 |
| Parking area | 24,480 |

The HVAC system of the considered SC provides three central functions of heating, ventilation and air conditioning. One special feature of the cooling supply system, is the integration of a geothermal field for cooling. In accordance with the environmental requirements, the maximal cooling power is 2000 kW. Furthermore, four electrically driven chillers, each with 600 kW, are part the cooling supply system.

District heating is used for heat generation. Two substations, each with 1,350 kW, supply the system with thermal power.

The air conditioning is provided via 11 air handling units (AHUs) with a total air flow rate of 410,000 $\frac{m^3}{h}$. Mainly, the heat removal is provided by the mentioned all-air system. Additionally, the tenants have the option to install standard air-water systems (ACUs), which operate with low supply temperatures.

In order to grasp the energy demand structure of the present SC, to analyze the system operation and to develop methods for operation optimization, a concept of an energy- and operation-monitoring was implemented. At the current state, usable monitoring data is only available on monthly basis for the annual energy demand (energy monitoring).

## Method

For the simulation of a building energy system different models have to be used. Firstly, the building model represents the demand side. The heating and cooling load as well as the indoor air temperature are the required output variables. Furthermore, the model must take into account that the areas within a SC building are used for various purposes, e.g. sales areas, restaurants, etc. Secondly, models of heat and cold generation, distribution, transfer and control need to be coupled with the building. Finally, for the integration of renewable energies, suitable sink and source models need to be integrated into the overall energy system model. All these models are interconnected in the object-oriented modeling language Modelica with the development environment Dymola.

### Building model

For modeling large multi-zone buildings, a reduced order model approach is used. The applied building model is developed by Lauster et al. (2014) for the dynamic simulation of different thermal zones and is available at the open-source Modelica library AixLib (Fuchs et al., 2015). This model combines the building physics and the models for internal gains, which are given by persons, lighting and machines. Here, the building physics model is based on the German Guideline VDI 6007 (The Association of German Engineers, 2012). According to the guideline, the thermal behavior of a building can be described by the interconnection of electrical resistances and capacities in analogy to an electrical circuit. The resistance-capacity model uses three capacities for a thermal zone, in each case for outer walls, inner walls and the air node, see Figure 1. Furthermore, the model uses two resistances for outer walls and only one resistance for inner walls, as they are assumed to be adiabatic. The resistances between the walls represent the radiative and convective heat transfer. Due to the small number of parameters and equations, the computation time is reduced significantly compared to more detailed (high order) building models, while the main thermal properties, as well as the heat transfer mechanisms of a building are completely taken into account.

The internal gains are modeled as heat sources, which are interconnected with the air node. The heat transmission of each internal gain comprises a convective and radiative component, with a convective share of 50 % for lighting and persons, and 60 % for machines. The load of each internal gain is determined by an external input, which can be a constant value or an occupancy schedule. Ventilation is considered as a convective heat sink, which is interconnected with the

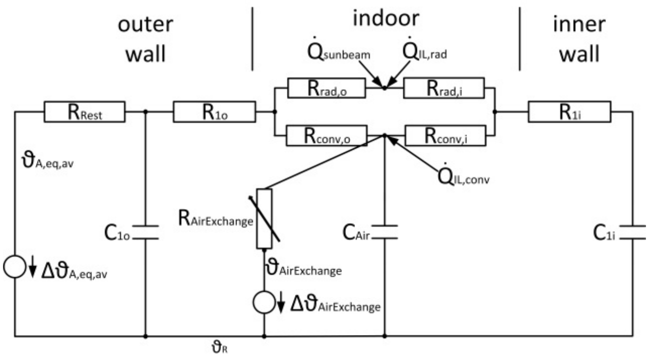


*Abbildung 1: Thermal Resistances and Capacities of Building Model based on VDI 6007*

air node. The energy balance is described by equation (1). The air temperature is assumed to be homogeneous within the thermal zone and heat sources and sinks are effective in the entire zone.

$$\dot{Q}_{ventilation} = \dot{m}_{supply} \cdot c_{p,air} \cdot (T_{supply} - T_{room}) \quad (1)$$

**Parametrization**

Due to the chosen modeling approach, the building data set is not directly usable for the parametrization of the building model. For this purpose, it is necessary to calculate the resistances and capacities based on information from the sizes and physical properties: density, heat capacity and thermal conductivity of the building construction. For this step an open-source software tool called TEASER is applied (Remmen et al., 2016). TEASER aims not only at calculating the necessary parameters for the building model from known building properties, but also features a database of typical building setups based on statistical data. This provides the opportunity of a quick parameterization of archetype buildings (e.g. office building, laboratory) with little input data like year of construction, floor area, and usage type. With the ability to export the model parameters in a structured way, using the Modelica record type, which can be automatically imported into the model, this information can be used to set up the building model directly.

An archetype building for SC is not developed yet and is the focus of the on-going work. To benefit from the quick parametrization of such an archetype building, the archetype office building has been modified. Both, SC buildings and office buildings show a multi-zone structure. The input data for the parametrization of an archetype office building is:

- year of construction
- construction type
- number and height of floors
- net leased area
- zone area factors
- zone layout
- window layout
- gross factor
- ventilation

where the parameter year of construction indicates the typical heat transition coefficient of the building envelope and specifies the typical building structure according to the age class of the building. The parameter construction type indicates the level of thermal mass, either high or low. The parameter number of floors influences the calculation of the building envelope areas as well as the thermal mass of the building. The parameter gross factor is also used for calculation of the building envelope areas. The window layout is used to determine the window area. Three different window layouts are distinguished, which describe the share of windows on the facade of the building. The area factors of the zones, determine the shares of the zones on the total net leased area. With the indication of the height of floors, the volumes of zones and the volume of the entire building can be calculated. The parameter zone layout determines the zone geometry, as well as the share of the building envelope area. Three different zone layouts are being distinguished. The compact layout represents zones with a square base area. the second and third layout represent a zone with a rectangular base area. The difference between this two layouts is their aspect ratios. The parameter ventilation is a Boolean value and determine, whether the ventilation is mechanical or natural. In case of mechanical ventilation, TEASER adds the needed parameter for a central AHU to the Modelica record.

*Tabelle 2: Characterizations of the considered shopping center - building geometry and physics*

| | |
|---|---|
| Year of construction | 2008 |
| Construction type | heavy construction |
| Number & height of floors | 3 floors, h=3.2 m |
| Net leased area | 34846 $m^2$ |
| Zoning | see Figure 2 |
| Zone layout | elongated, 2 floors |
| Window layout | 10 % of facade area |
| Gross factor | not available |
| Outer walls area | 8646 $m^2$ |
| Roof area | 10363 $m^2$ |
| Floor area | 10363 $m^2$ |
| Ventilation | mechanical |

Table 2 shows the parameters of the considered SC, which are based on the planning documentation. The considered building was constructed in the year 2008. According to the reinforced concrete structure of the building, the level of the thermal mass is assumed to be high (heavy construction). For classification of the thermal zones, zone related information like room area and the intended use of each room where extracted from the floor plans of the planning documentation. Subsequently, predefined use conditions were assigned to each room. The use conditions are based on the German standard DIN V 18599 (Deutsches Institut für Normung, 2016). Distinguishing features of the different use conditions may be the set temperatures, air exchange, occupancy profiles, inner loads and other related attributes. Consequently, all rooms with an equal or similar use condition were summarized into one thermal zone. Figure 2 shows the resulting zones of the considered SC. Here, the zone shops summarize the sectors clothing, accessories, general store, body care and health, hobby and leisure, home decor and services. The use condition of the SC mall is assumed to be similar to that of a common room, because of the continuous customer presence during the opening hours.

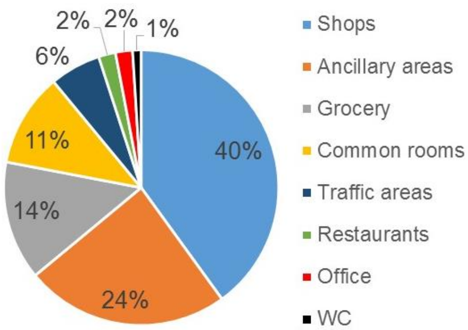


*Abbildung 2: Zoning of the considered shopping center: allocation of the net leased area*

In the present work, the internal loads are represented by schedules that reflect the occupancy and usage of equipment like machines and light. The occupancy schedules are based on the German standard DIN V18599 and SIA 2024 (Deutsches Institut für Normung, 2016) (Seidinger and Ménard, 2006) and adapted to the considered SC. For each zone a day profile is defined. The annual occupancy is represented through the periodically repetition of this day profile, whereby the non-operating days, as well as the actually opening hours are considered. Figure 3 shows exemplary the day profiles of the zones shops and grocery. During the week, the considered SC is open from Monday to Saturday. In case of the grocery stores, the opening hours are 7.00 - 20.00, whereas the opening hours of the shops are 09.30-20.00. For the definition of day profiles of the zones shops and grocery, the following assumptions are made: first of all the staff of the SC need to stay longer than the opening hours for cleaning up and make preparations for the next day. Secondly, the staff of grocery stores needs in general a longer preparation time than in the remaining stores, because of daily dealing with fresh food. Thirdly, the loads through lighting and machines are constant during the opening hours and without people present no lighting is needed. Finally, a base load through the entire year is caused by the machines and due to the refrigerated shelves, the loads through the machines in the zone grocery are assumed to be higher than in the zone shops. Since there is no reliable information about the installed capacities of lighting and machines in the considered SC, the loads are derived from the current annual electricity consumption of the selling areas, as the consumed electrical power of the devices and lighting is transformed to heat. Here, the average daily consumption is calculated first. Then, the average daily consumption is spread over day, considering the opening hours, the aforementioned assumptions and the fact that the highest heat input in SC is resulting from the lighting. The actual occupancy profiles of customers of the considered SC are unknown, only the annual visitor number is known. In order to define the occupancy day profiles, the average daily visitor number is calculated first. Secondly, the daily visitor number is spread over the opening hours assuming two peak times per day, one at midday and one in the evening.

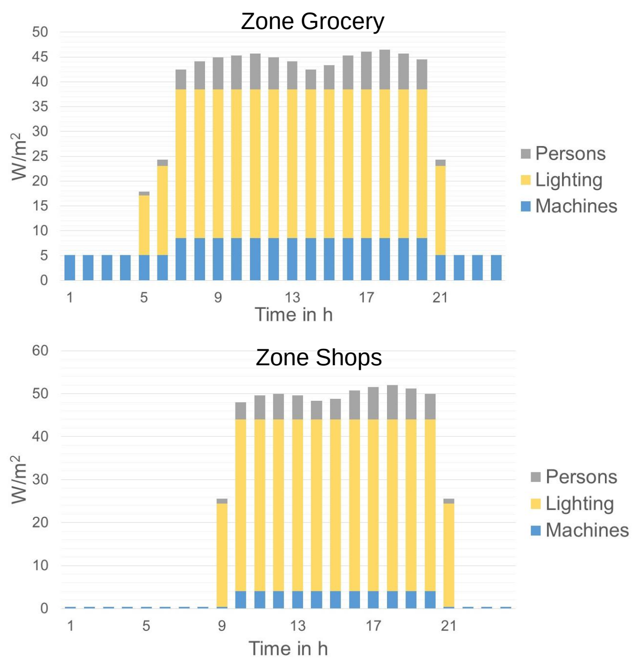


*Abbildung 3: Occupancy day profiles of the zones shops and grocery*

For the zones common rooms, restaurants, ancillary areas, WC (sanitary facilities) and traffic areas, the occupancy schedule is only adapted to the opening hours and the number of visitors. The occupancy of the zone office is assumed to be independent from the number of visitors.
The thermal boundary conditions are represented by the indoor comfort temperatures of the individual zones, air change rates of the individual zones and the conditions for the supply air. For the considered SC, there is no information available neither on the set and the actual indoor temperatures, nor on the supply air conditions. Furthermore, the supply air conditions are in general not constant. According to the

requirements and desires of the user, the technical stuff adapts the set values. For modeling, the indoor comfort temperatures of the individual zones are taken from the German standard DIN V 18599. These temperatures are used as set points for the controller of the heating and cooling devices.
To define the air change rates, it is assumed that the fresh air supply is only provided by the mechanical ventilation. Based on the planning documentation, the entire volumetric air flow rate through the AHU is subdivided into the individual zones. Table 3 shows the air change rates of zones.

*Tabelle 3: Air change rates of zones*

| Zone | Air change rate in $\frac{1}{h}$ |
|---|---|
| Shops | 6.25 |
| Ancillary areas | 0.2 |
| Grocery | 5 |
| Common rooms | 3 |
| Traffic areas | 0.5 |
| Restaurants | 5 |
| Office | 1 |
| WC | 4.7 |

**HVAC models**

In addition to the building model, models of HVAC system components are needed for modeling the entire BES. Therefore, a Modelica library that allows a fast composition and simulation of building energy systems is used (Stinner et al., 2015). The models of air-water systems, chiller and geothermal field are not included in this library and had to be modeled additionally.
Since supplementary air-water systems are used in order to handle the comparably high internal loads within the selling areas, it is necessary to extend Lauster's building model by an air-water system model. The developed air-water system model is able to represent circulating air cooling units (ACUs) and active chilled beams (ACBs). Both systems have an air-water heat exchanger where the circulating indoor air is cooled. In case of the ACUs, the circulating air flow is propelled by a fan. ACBs use the momentum of the primary air flow rate (preconditioned fresh air), which is delivered through multiple small nozzles to entrain a secondary air flow rate (circulating room air).
Due to the used building physics model, where the entire indoor air is represented by only one node, the temperature change of the secondary air flow rate needs to be determined initially by the air-water system model using the following equation:

$$T_{sec} = T_{room} + \frac{\dot{Q}_{cooling}}{c_{p,air} \cdot \dot{m}_{sec}} \tag{2}$$

where $\dot{Q}_{cooling}$ is the heat flow that is transferred from the secondary air flow to the cooling circuit in the air-water heat exchanger.
Subsequently, the supply air temperature is calculated using the equation (3) and is used as input for the building physics model, see equation (1).

$$\dot{m}_{supply} \cdot T_{supply} = \dot{m}_{sec} \cdot T_{sec} + \dot{m}_{prim} \cdot T_{prim} \tag{3}$$

$\dot{m}_{prim}$ is the mass flow rate of fresh air, which is preconditioned by the AHU with the set temperature $T_{prim}$.
The overall mass flow rate of the supply air is:

$$\dot{m}_{supply} = \dot{m}_{sec} + \dot{m}_{prim} \tag{4}$$

In case of the ACU, the secondary air flow of the air-water system model can be specified directly with a settable parameter. In case of ACB, the secondary air flow is entrained by the primary air flow. This feature can be described by the induction ratio $I$, which is defined as:

$$I = \frac{\dot{m}_{sec} + \dot{m}_{prim}}{\dot{m}_{prim}} = 1 + \frac{\dot{m}_{sec}}{\dot{m}_{prim}} \tag{5}$$

The cooling power of the air-water system model is controlled by the mass flow rate of the cold water circuit. Firstly, an integrated two-point-controller observes the room temperature and provides an ON/OFF signal to the water pump. Secondly, the mass flow rate of the water pump is set ideally by a PID-controller, depending on the temperature difference between the set and the current room temperature.
The considered SC is equipped with 11 AHUs, which supply different premises of the building. In order to model the entire building energy system, for simplification purposes is assumed that the entire building is supplied by one centrally installed AHU. The simplification has a positive effect on the computation time, as well as the time to set up the model. The applied AHU model is particularly developed for fast simulation of centrally installed AHU in buildings (Mehrfeld et al., 2016). The AHU is modeled as a multi-mode model. In Modelica this approach is represented by state machines. In order to provide the required supply air conditions, the model uses static enthalpy based equations for discrete time steps for calculations of required thermal capacity. In particular, the thermodynamic functions of an AHU like heating, cooling, humidification and dehumidification are balanced, based on the enthalpy flow of moist air. The electrical demand of the fan is calculated by the overall pressure drop of the ventilation system and the transported air volume. The model of Mehrfeld et al. (2016) shows a reasonable computational effort, while getting profound result accuracy. For distribution of the centrally handled external air to the individual zones, a splitter model is used. The splitter model divides the incoming overall air flow into predefined air flows. Consequently, the supply air conditions for each zone are identical.

The supply air conditions are defined by the determination of the minimal and maximal supply air humidity and the heating and cooling temperatures. Since there is no proper information on the set conditions for the supply air, the conditions are defined with assumed values. The values of temperature and humidity for the cooling and heating mode are summed up in Table 4.

*Tabelle 4: Supply air conditions - set points for heating and cooling mode*

| | Heating mode | Cooling Mode |
|---|---|---|
| $\varphi$ in % | 38 | 93 |
| T in °C | 22 | 16 |

In the present work, a geothermal field is used for cooling or pre-cooling of the cold water circuit. The geothermal field is modeled as an ideal thermal sink. Thus, the set temperature of the output is always achieved. The needed cooling power as the output, is calculated by the sink model.
The main requirement for the electrically driven chiller model, is the dynamic simulation of the energy efficiency ratio (EER). The sub-model for dynamic EER simulation is based on the European Standard EN255 and EN14511 (Deutsches Institut für Normung, 1997), (Deutsches Institut für Normung, 2012). Here, the manufactures indicate the EER for several operating points. The operating points are specified by the input temperature of the condenser and the outlet temperature of the evaporator. The condenser and evaporator are modeled as a heat sink or heat source respectively.
The considered SC is connected to a district heating supply system. In this paper, the district heating substation is assumed to be ideal. Therefore, the heat supply is represented by a heat source model.
The static heating system in each zone is represented by an ideal heater model. The ideal heater model is modeled as a heat source, which is controlled by an integrated PI-controller. The heater model is directly interconnected with the air node of the building model, without any heat transfer resistance. Thus, the set temperature is always maintained.
External loads, such as climate and weather conditions can best be estimated by detailed information like local weather data. Especially in model validation, deviations due to insufficient weather data should be eliminated by using exact information. In case that the exact weather data is not available, data given in Test Reference Years (TRY) can be used (DeutscherWetterdienst DWD., 2011). The weather model reads the data set as input and generates the desired outputs. The region 13 of the TRY data set is representative for Munich. The desired outputs are the air temperature, long wave sky and terrestrial radiation, wind speed and as the building is equipped with an AHU, mass fraction of water in the dry air.

**Supply system variants**

The presented modeling approach focuses on the development of energy efficient supply concepts of SC. In this paper, three different variants of cooling supply systems for the considered SC are investigated. The first system variant represents the conventional cooling supply system. Here, the SC building is equipped with an AHU and additional ACUs in the zones shops and grocery. The electrically driven chiller is the only cold generator within the cooling supply system. Figure 4 shows the schematic representation of the system. Both, the AHU and ACUs are supplied by the same cold water circuit. Based on the planning documentation, the cold water set temperature is set to 9 °C. A splitter model spreads the incoming mass flow rate to the AHU and the ACUs of the individual zones. Consequently, the flow temperatures for the AHU and the ACUs are identical. The return temperature of the cold water circuit is calculated based on the incoming mass flow rates of the AHU and ACUs and the corresponding temperatures. The refrigerant circuit and the cold water circuit are coupled by a heat exchanger. For the heat transfer between both circuits, a temperature difference is needed. Therefore, the set value for the refrigeration circuits flow temperature is set to 7 °C.

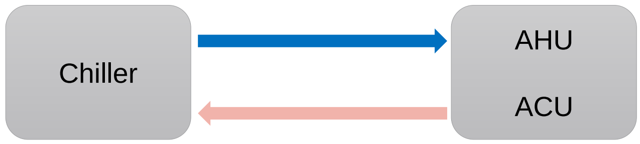


*Abbildung 4: System variant 1 - Conventional cooling supply system*

The second system variant is the extended conventional cooling supply system by the integration of a geothermal field. This system corresponds to the cooling supply system of the considering SC. Here, the geothermal field is applied for pre-cooling of the cold water circuit. As mentioned before, the temperature of the geothermal field model outlet is ideally settable. Based on planning documentations, the set temperature is set to 13 °C. The required cold water temperature of 9 °C, is achieved by additional cooling power of the chiller. Figure 5 shows the schematic representation of the second system variant.
The new concept for ventilation of SC (Mathis et al., 2015) is implemented into the third system variant. According to the ventilation concept study, the air change rates in show rooms are reducible down to 1.1 $h^{-1}$ without deteriorating the air quality. The newly developed ACB is able to operate with low air change rates and simultaneously with elevated cold water supply temperatures, up to 18 °C. Consequently, the ACUs are replaced by the ACBs first. Secondly, the air change rates in the zones shops and grocery are reduced in two steps. The schematic representation

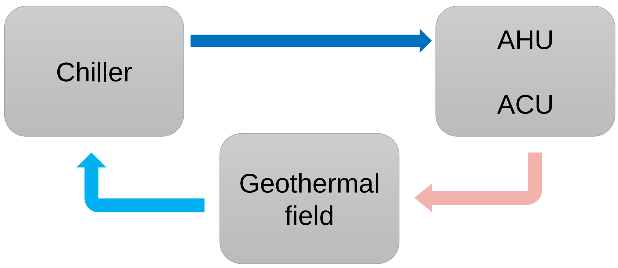


*Abbildung 5: System variant 2 - Conventional system extended system by a geothermal field*

of the third system variant is shown in Figure 6.

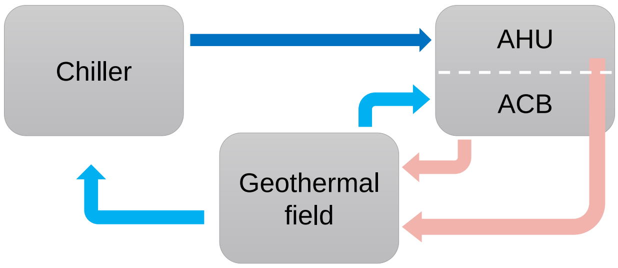


*Abbildung 6: System variant 3 - Implementation of the new ventilation concept*

The ability of the ACBs to operate with elevated cold water supply temperature enables the direct use of the geothermal field for cooling. Thus, the ACBs are supplied by a separate cold water circuit with a supply temperature of 13 °C.
In order to reduce the air change rate $r$ in the zones shops and grocery, the specific cooling power of the entire system must not fall below 55 $\frac{W}{m^2}$. This cooling power is needed to meet the thermal boundary conditions of the zones by removing the heat of the internal gains. In accordance to the case study, a constant induction ratio of $I = 7$ and an air change rate of $r = 2.4$ is sufficient to ensure the specific cooling power of the entire system of at least 60 $\frac{W}{m^2}$ under given boundary conditions ($T_{flow} = 13°C$, $T_{prim} = 16°C$). As a limiting case, the air change rate is reduced further to $r = 1.6$, without changing the other configurations. Moreover, through the installation of ACBs, the pressure drop of the entire ventilation system is raised by additional 150 Pa.

## Simulation results and discussion

Following the presented approach, the SC-BES is modeled and the simulated results are presented in this section. Firstly, the simulated thermal demand of the considered SC building is presented and compared to the monitoring data of the year 2015. Secondly, the annual primary energy demand (PED) for air conditioning of the presented cooling supply systems is compared and the saving potential of the new ventilation concept is presented. Therefore, the annual demand for air conditioning of each system variant is determined by simulation over a period of one year. Based on German primary energy factor for electricity and the factor for district heating in Munich, the PED for air conditioning is calculated. Table 5 shows the applied factors.

*Tabelle 5: Primary energy factors*

| | $f_p$ |
|---|---|
| Electricity | 1.8 |
| District heating, Munich | 0.11 |

Figure 7 shows the simulated cooling and heating load of the considered SC. With regard to the cooling load, a base load over the year of approximately 500 kW can be identified. The base load is resulting from the high thermal input of the internal gains, especially from the lighting. Additional cooling load is required in the warm season for cooling and dehumidification of the warm and moist external air. The regular loopholes in the load profile can be traced back to Sundays, when the SC is closed. The heating load is mostly needed in the cold season for heating and humidification of the cold, dry external air. The computational time is 567 seconds for the simulated period of one year with an output resolution of one hour on a desktop machine.
The simulated results are compared to the monitoring data. The available monitoring data contains monthly values of the cooling and heating energy consumption of the year 2015. In Figure 8, the simulated cooling demand is compared to the measured consumption of cooling energy. The comparison shows that the simulated annual cooling demand is 19 % higher than the measured value. The comparison of monthly values shows that the simulated results tend to be higher than measured consumption. Especially during the cold season the simulated data shows significant deviations from the measured data. Also the simulated heating demand is significantly higher during the cold season than the measured heat consumption, with regard to monthly values. The deviation of the annual heating demand and the actual consumption is almost negligible, see Figure 9.
The deviation between the simulation results and the measured data can be traced to the simplifications of the presented approach. Another reason for the deviation is the applied weather data set. Instead of the actual weather data (Munich 2015), the test reference year data set is used. Also, the missing information about the actual system settings, actual asset operation, visitor frequency and indoor temperatures have a negative impact on the repeatability.

### System comparison - primary energy demand for air conditioning

The PED for air conditioning is composed of the expenses for ventilation, water pumping and the gene-

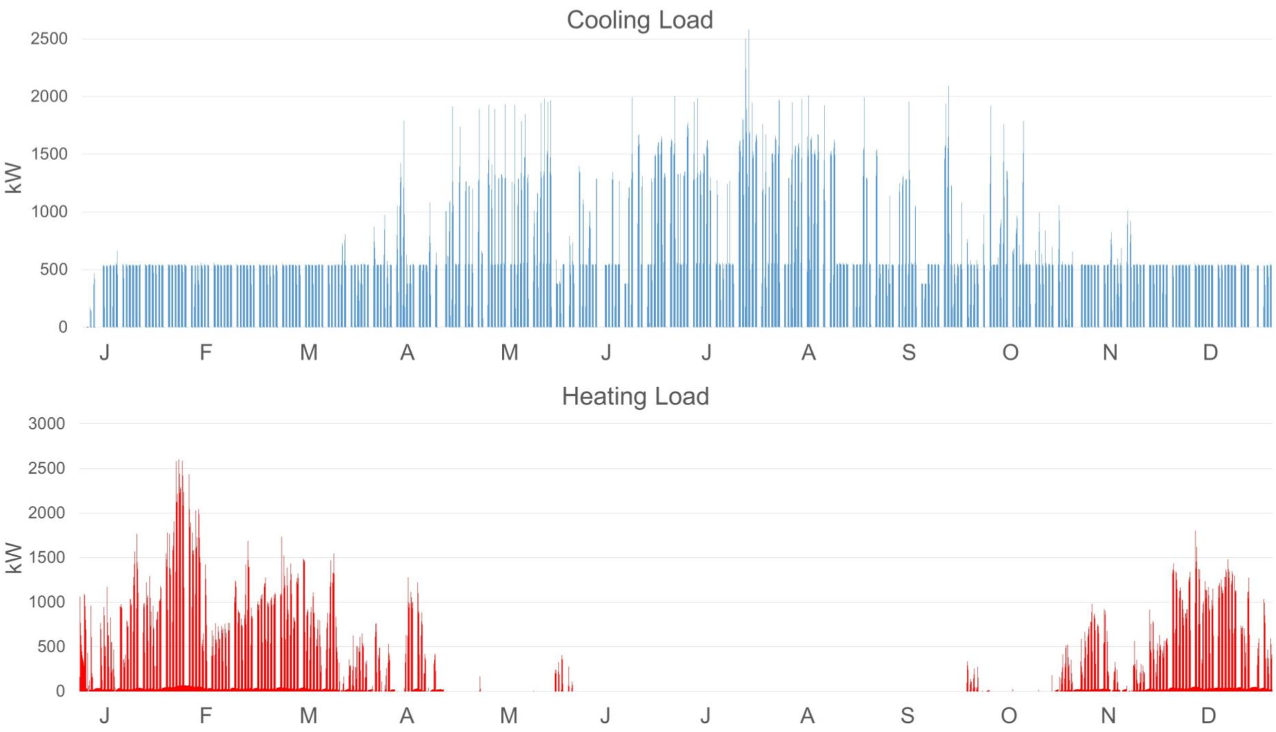


*Abbildung 7: Simulated annual cooling and heating load with hourly resolution*

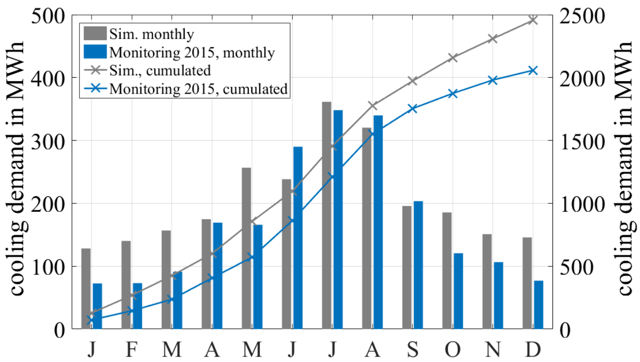


*Abbildung 8: Comparison of measured data of 2015 and simulation results - Cooling demand*

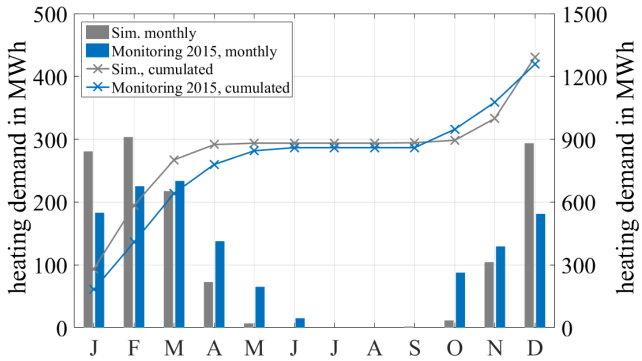


*Abbildung 9: Comparison of measured data of 2015 and simulation results - Heating demand*

ration of the heating and cooling energy. Figure 10 shows the specific energy demand for air conditioning of the investigated systems. Here, the energy demand is referred to the net leased area of the considered SC.

The results show that the main consumers of the conventional system are the ventilation with 62 % and the electrically driven chiller with 28 %.

With the integration of the geothermal field, the consumption of the chiller is reduced. Simultaneously, additional electricity is consumed by the pumps of the geothermal field. In total, by this measure the PED is reduced by 5.6 %.

Considering the results of the third variant, the significant saving potential of up to 30.4 % of the PED can be identified. The reduction of the air change rate effects that the transported air volume is reduced. On the other hand, with the installation of ACBs, the pressure drop of the entire system is raised. In total, the share of the annual expense for ventilation is decreased by this measure to 48 %. Another apparent effect is that the heat removal is increasingly shifting to the cold water circuit. Thus, the water pumps are one of the main consumer of the system with 45 %. The expense for generating cooling energy by the chiller with 4 %, plays a tangential role.

With further reduction of the air change rates, the annual PED for air conditioning can be reduced potentially by up to 35.1 %. With a share of 53 % of the PED, the water pumps are the main consumer in the cooling supply system, followed by the ventilation with 41 %.

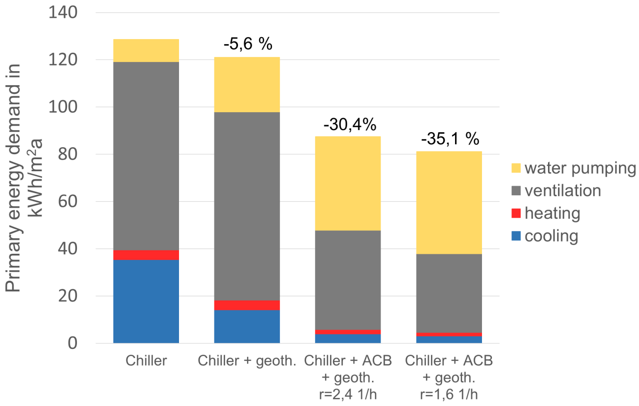


*Abbildung 10: System comparison - annual primary energy demand for air conditioning*

## Conclusion and further work

In this paper, a modeling approach for shopping center (SC) building energy systems (BES) in Modelica is presented. Models for the SC building and the applied HVAC-models are introduced. The simulated thermal demand is compared to the monitoring data of the year 2015 of an existing SC on monthly basis. Following the presented approach, three different variants of cooling supply systems are modeled. In order to compare the energy efficiency of these systems, the primary energy demand for air conditioning is determined by annual simulations.

The comparison of the simulated thermal demand with the measured data shows that the model is able to reproduce the values of monthly and annual thermal demand of the considered SC. An annual simulation with an output resolution of one hour is obtained in 567 seconds on a standard desktop machine. Thus, the presented modeling approach provides the opportunity for a very fast dynamic analysis and simultaneously an accurate enough prediction of the annual energy demand. It is suitable for the investigation of different cooling and heating energy generation concepts and their mutual interaction. Furthermore, different types of buildings with different boundary conditions can be investigated (e.g. locations) in a time efficient manner.

The simulation results show that measures like elevating the cold water cycle temperatures, reducing the air change rates and the integration of geothermal energy for cooling could reduce the primary energy demand for air conditioning potentially by up to 35 %. In order to develop optimized energy systems for future SC, further concepts of SC-BES need to be investigated. Furthermore, the model will be used for evaluation of system components, system control strategies and energy saving measures, like shifting to LED lighting in show rooms. Simultaneously, based on more detailed monitoring data, the current models will be improved by calibration in order to enhance the result accuracy.

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