A Representative Simulation Model for Benchmarking Building Control Strategies

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Abstract –

To increase the energy efficiency of building energy systems, many control strategies have been investigated in recent years. Researchers apply control strategies to different building energy systems in order to evaluate their performance. However, the scientific community lacks a commonly accepted reference building model and evaluation criteria.

In this paper, we therefore propose a simulation-based benchmark to rate different control strategies for building energy systems. Based on identified requirements for benchmarking, we design a building model on which researchers can apply different control strategies and compare them with each other. The building consists of five different rooms and an energy system with several heat and cold generators. A concrete core activation and a central air-handling unit with additional decentralized cooling and heating registers supply each room individually. To benchmark a control strategy, the model calculates the consumed energy, the primary energy costs and the indicators of indoor air quality. We apply the benchmark to two different control strategies. The benchmark provides reproducible quantitative assessments of the performance of the tested control strategies. The diversity of the energy system as well as the individual air-conditioning of the rooms allow complex and sophisticated control strategies to demonstrate their potentials.

Keywords –

Building control strategies; Building automation; Benchmark; Modelica

1 Introduction

In the last decades, plenty of control strategies, e.g. Model Predictive Control (MPC), Fuzzy Logic Control, Neuronal Network Control and Cyber-physical control [1], promised to increase the efficiency of building energy systems in order to reduce CO_2 emissions and energy consumption [2]. To evaluate the developed control strategies, many researchers compare the developed control strategy with a standard control strategy such as On/Off control, PID control [3] or an ideal controller [4]. They point out the achieved savings with the newly developed control strategy in comparison to the standard one. However, the scientific community lacks a commonly accepted model for benchmarking control strategies. The controlled energy systems as well as the reference control differ in almost all case studies. Thus, the calculated performance or relative energy savings for newly developed control strategies are not comparable with each other.

The focus of this work is the design of a building model including its energy system that serves as the core of a benchmark for control strategies in the building domain. Additionally, we propose evaluation criteria in order to rate the achieved performance. We implement the designed building in the modeling language Modelica in order to provide a simulation based benchmark.

1.1 Related Work

To rate the performance of a controller, researchers commonly use criteria like the IAE (integral of time-multiplied absolute value of error) or the ISE (integral squared error), especially in control theory or PID tuning [5]. Nevertheless, other criteria are of greater importance in the building sector. DIN EN ISO 50001:2011 [6] defines benchmarking as a process of analyzing and comparing power data of comparable activities with the aim to compare the energy-based power data. Besides the energy consumption, criteria like carbon emissions, indoor air quality [7] or operation costs [8] are research topics. Recent work focuses on methods to benchmark the operation of a building based on the above-mentioned evaluation criteria. Borgstein et al. [9] present static, dynamic and statistical methods in order to calculate the energy consumption of non-residential buildings. Du et al. [4] developed an exergy-based method to calculate the theoretical minimal energy consumption to compare it with the energy consumption of the tested controller. However, all methods lack a specified building model, which other developers could use to rate their control strategy and compare them with each other.

Sänger et al. [10] suggest an approach to tackle this problem: they developed a toolchain for benchmarking control strategies. Within the toolchain, the user can select different building types and create a control strategy. The control strategy consists of different combinable blocks and modules (e.g. hysteresis). However, the proposed toolchain does not support complex and advanced control strategies (e.g. MPC).

2 Benchmark Model

Benchmarking is a method frequently used in the information technology (IT) to quantify the performance of a computer, central processing unit (CPU) or graphics processing unit (GPU). According to Gray [11], domain-specific benchmarks are needed that are tailored to the system to be tested. For instance, a benchmark in the IT domain is not directly applicable to a benchmark for building control strategies. Nevertheless, Gray defined four general key criteria for a domain-specific benchmark, which we will transfer to the building controller domain:

- Relevant
- Portable
- Scalable
- Simple

Relevant means that the benchmark calculates relevant criteria (e.g. performance or price in the IT domain). A benchmark is portable if it is applicable to different systems. Additionally, the benchmark must be scalable to large and small computer systems in the IT domain. Finally, the benchmark has to be understandable (simple). [11]

In building domain, a relevant benchmark has to include typical building operations and measure the performance of the system in a relevant unit, e.g. energy consumption. Portable means in our use case that the benchmark is applicable to different control strategies. A scalable benchmark allows the evaluation of controllers of different size or complexity. To be understandable, the controller decisions have to lead to reasonable reactions in the performance measurement.

2.1 Benchmark Requirements

A benchmark for building control strategies should fulfill the above-mentioned criteria. To provide portability and scalability, we developed a simulation-based benchmark. In contrast to a real-life experiment, a simulation can produce reproducible boundary conditions, e.g. weather or occupancy, and is often executable at a lower price. In order to develop an understandable (simple) benchmark, we design the building model based on standards and real-life data.

In general, a benchmark measures the performance of a specific task, e.g. the needed time for mathematical operations. The complexity of the task has a major impact on the meaningfulness of the benchmark. For instance, measuring millions of instructions per second cannot point out the potential of a multi-core CPU in comparison to a single-core CPU [11].

Transferred to our case, controlling the building and its energy system is part of the tasks the controller needs to solve. The task's difficulty and thus the complexity of the building needs to be sufficiently high: a simple task could be solved with a sufficient accuracy even by poor control strategies. For instance, a building has less optimization potential, if its building energy system (BES) includes only an electric heater without any heat storage. Another example for a simple system is a room that has low requirements regarding the thermal comfort.

A simple benchmark system will not identify the potentials of sophisticated and advanced control strategies. Therefore, the complexity of the energy system as well as the requirements for thermal comfort need to reach a certain level. However, the complexity of the system must not exceed an engineer's understanding to create an understandable/simple benchmark.

2.2 Building Type

In general, buildings can be divided into residential and non-residential buildings. Residential buildings account 75 % of the net floor area and consume 68 % of the total final energy use in buildings in Europe [12]. The energy systems of European residential buildings are often simple and often provide only heat. Non-residential buildings contain a higher amount of different energy generation and distribution components including heating, cooling, ventilation, and air-conditioning (HVAC), which makes them more interesting for the benchmark.

In Europe, 28 % of the area of non-residential buildings belong to wholesale and retail buildings, 23 % offices, 17 % educational buildings, 11 % hotels and restaurants, 7 % hospitals, 4 % sport facilities and 11 % other buildings [12]. In our opinion, wholesale/retail buildings and offices are most relevant because of their large percentage. Furthermore, the advantage of offices are standards concerning the area and climate comfort. Offices usually consist of several rooms with heating, cooling and air conditioning. Thus, their energy system provides the necessary complexity for our purposes. Additionally, office rooms have high disturbances, e.g. changing internal gains due to occupancy and solar radiation, especially if there is a high share of glass in the facades. The disturbances set a difficult task to the controller in order to keep the set-point temperatures and humidity in a certain range.

Therefore, we chose an office building as the building type for the benchmark model.

2.3 Building Physics

The building model should consist of typical rooms in order to be relevant and understandable. In contrast to a real building, the number of rooms needs to be smaller in order to achieve a scalable and simple benchmark. If the number of rooms exceeds, it would take a lot of work and time to apply a control strategy to the benchmark.

The ASR A1.2 [13] describes different room types and their typical area, usage and number of persons. We consider large-scale office rooms as open-plan office rooms and both single offices and small multi-person office rooms as shared offices rooms. Conference rooms are special regarding the space requirements and occupancy. The fluctuating occupancy leads to high changes of the internal gains. Additionally, the set-point temperatures and humidity can vary during the day, e.g. if the room is empty for some hours.

Further room types that are common in office buildings are hallways, stairways, toilets, entrances and storage rooms. Due to the short time a person stays in these rooms, the climate comfort is less relevant, and the internal gains are approximately constant. Hence, we do not include any of these rooms.

In order to provide rooms with different comfort requirements, temperature levels and internal gains, we added a workshop and a canteen to the benchmark building. Workshops and canteens require, due to emissions, a high ventilation rate, which makes them interesting for our benchmark.

All in all, the benchmark building consists of five different rooms with typical specifications for the selected room type:

- Open plan office
- Shared office
- Conference room
- Canteen
- Workshop

Each room has different requirements regarding usage, energy demand and comfort. Figure 1 shows the floor plan. The dimensions of the rooms are based on ASR A1.2 [13]. The height of the rooms is three meters.

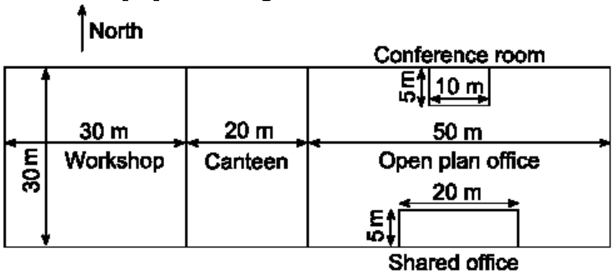

Figure 1. Floor plan of the benchmark model

2.4 Building Energy System

The energy system aims to heat, cool and ventilate the building in order to achieve a comfortable climate in the rooms. The energy system of our model should contain typical components to be relevant and understandable. Additionally, the energy system should cover the requirements concerning its complexity. Figure 2 illustrates the designed energy system. In the following, we describe the design of the energy system.

Each of the five rooms of the benchmark building contains a ventilation unit with heating and cooling registers in order to supply the room with conditioned air. A central air-handling unit (AHU), which consists of a heater, cooler and humidifier, supplies the decentralized ventilation unit. Additionally, each room can be heated and cooled by a concrete core activation (CCA).

In order to supply the concrete core activation, the air-handling unit and the decentralized ventilation units with heat and cold, the energy system provides hot water at two temperature levels (high temperature and low temperature) and cold water at one temperature level. A boiler and a combined heat and power unit (CHP) produce heat at the high temperature level. The CHP offers an efficient simultaneous electricity and heat production, but its operation is bounded by minimal on and off times. In contrast, the boiler can be switched on and off faster to respond to a changing demand more dynamically. Both the CHP and the boiler are supplied with gas.

A central element of the energy system is a heat pump. The heat pump produces low temperature heat as well as cold for the cold-water supply. A geothermal field as well as an outside air heat exchanger with a fan serve as a heat source. The geothermal field provides a constant temperature (13 °C) whereas the outside temperature fluctuates. Thus, depending on the outside temperature, using the geothermal field or the outside air as a heat source is more efficient.

The geothermal field and the outside air can be used for free cooling as well; if there is only a small cold demand, the building can be cooled without using the heat pump. Additionally, the outside air serves as a heat sink for the heat pump.

In order to decouple the heat/cold generation and the consumption, the system contains one storage at each temperature level. The high temperature and low temperature heat storage can be used at two temperature levels; both can be supplied by either the heat pump or the CHP and boiler. The three storages allow a flexible operation of the heat/cold generators, thus predictive control algorithms could show their potentials.

Besides the thermal generators and consumers, the benchmark building contains electrical components. The CHP and a photovoltaic system (PV) produce electricity. The produced electricity can be fed into the grid or used for the building operation. Electrical consumers in the building are the heat pump, the air-handling unit, fans, pumps and all appliances inside the building such as computers and lights. The electrical consumption of the energy system is directly influenced by the control actions, whereas the consumption of the appliances inside the building is based on the occupant behavior (see section 2.5).

We dimensioned the heat/cold generators and consumers as well as the piping network according to DIN EN 12831 [14]. In a first step, we need to define the placement of the building. We chose the region 12 around the city Mengen in Germany because of the unsteady weather with higher temperature peaks in comparison with other regions of the DIN EN 12831. Based on the weather conditions, we determine the heat demand according to DIN EN 12831. The static heat demand for the whole building amounts to 94.5 kW. In order to use a night set back, which allows the reduction of the room temperature to 15 °C, an additional heating power of 139.7 kW is needed for reheating the building.

The calculated cooling demand is 166.7 kW according to DIN V 18599-2 [15] and DIN V 18599-10 [16]. The concrete core activation and the ventilation units cover equal shares of the cooling demand.

Based on the calculated demands, the pipe and air duct diameters can be specified according to DIN EN 10255 [17]. According to Laasch et al. [18], we assume a maximum water flow velocity of 2 m/s in the pipes and a maximum air flow velocity of 4 m/s in the air ducts.

Based on the heating and cooling demand, we defined the power of the boiler, CHP, heat pump and outside air heat exchanger.

The photovoltaic system fills half of the roof area and the power of the AHU fans is assumed to be 3 kW/(m^3/s) [19, 20]. Table 1 lists the power levels of the components. The electrical power of the 24 pumps are in the range of 75 W up to 4700 W.

The storages allow decoupling heat/cold generation and consumption. In order to provide a flexible and predictive use, we dimension very large storages. The two heat storages are able to cover the heat demand for the reheating of the building. Each heat storage has a volume of 22 m^3. The cold storage can cover the maximum cold demand for three hours and has a volume of 46 m^3.

In summary, the energy system consists of 30 valves, 24 pumps, a central ahu and the components boiler, CHP, heat pump and outside air heat exchanger with a fan that have to be controlled.

Table 1. Power of the components

Component	Power in kW
Boiler	19.9 – 66.2 (thermal)
CHP	46 (thermal), 26 (elect.)
Heat Pump	96.6 – 193.2 (thermal)
Chiller	67 – 235 (thermal ΔT = 15 K)
PV	112.5 (elect.)
AHU Fan	10.1 (elect.)

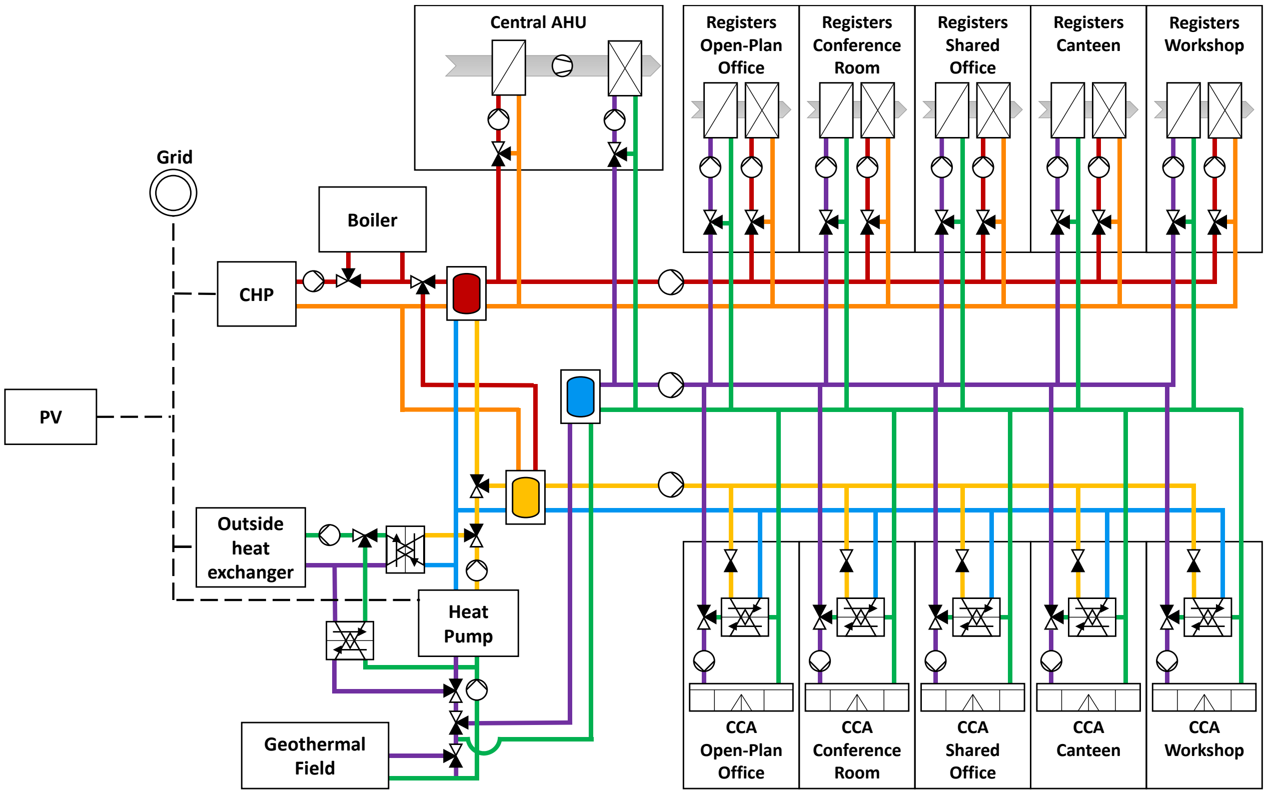

Figure 2. Energy system of the benchmark building model

2.5 Internal Gains

Internal gains are emitted heat caused by occupants and electrical appliances such as lighting and computers. Fluctuating internal gains challenge the controller to reach given set-point temperatures. Hence, we define varying occupancy profiles for each of the five rooms of the benchmark building. We assume five days per week with eight hours working time. In Germany, the absence of an employee per year is 20 days due to holidays [21] and 14.6 days due to illness [22]. We calculate the presence for each day with a probability distribution based on holiday and illness. The start time for the open plan office and the shared office is between 8:00 and 9:00 am, for the canteen between 8:45 and 9:15 am and for the workshop between 6:00 and 6:15 am. The arrival of each employee is random within the start times. The conference room is used randomly on an hourly basis. Figure 3 shows the resulting occupancy profiles for one exemplary day.

To calculate the produced heat of the occupants, we assume an activity level according to DIN EN ISO 7730 [23] of 2 met in the workshop and 1.2 met in the other rooms. The clothing level is 1 clo for all rooms and occupants. The resulting heat amounts to 209 W per occupant in the workshop and 125 W per occupant in the other rooms.

Based on the occupancy profiles, we calculate the electrical internal gains. In accordance with [24], we assume an illumination of 400 lx for the open plan office, the shared office and the conference room, 350 lx for the canteen and 500 lx for the workshop. Based on the floor area and an assumed luminosity of 95 lm/W [25], the lighting power amounts to 5684 W for the open plan office, 210 W for the conference room, 420 W for the shared office, 2210 W for the canteen and 4737 W for the workshop. Lights switch on if at least one person is present.

Laptops (20 W) and screens (30 W) cause further internal gains. We assume that laptops and screens are on if the associated employee is present. In the conference room, there are no screens available.

The power demand in the canteen is estimated in accordance with Renggli and Horbaty [26]. We add the minimum power for cooking (0.15 kWh/guest) to the power for cleaning (0.09 kWh/guest) and divided the result by the mean duration of stay (0.875 h). Since the study of Renggli and Horbaty is from the year 1992, we reduced the power consumption for cooking and cleaning by 22 percent. This value corresponds to the efficiency increase from class D to A [27]. The final power consumption in the canteen is 213 W/guest. In the workshop, we assume a power consumption of 200 W/employee for using tools.

We assume that the total consumed electrical power is converted to heat.

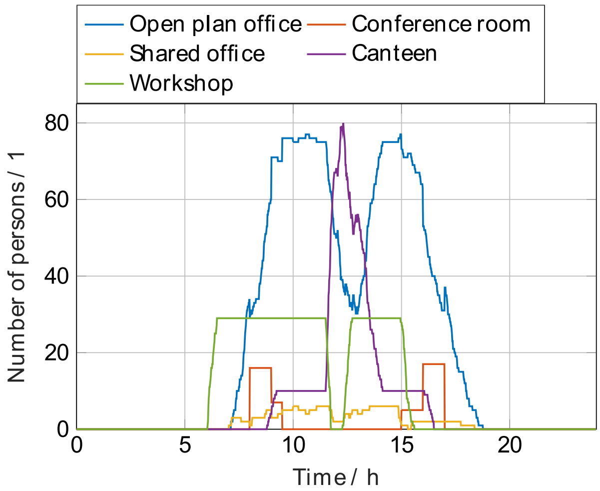

Figure 3. Occupancy profile of the building for one exemplary day

2.6 Weather

To set a difficult task to the controllers, the weather needs to have high fluctuation in order to disturb the energy system by a changing temperature and solar radiation. To achieve this, we use weather data from the city Mengen in Germany. In order to keep the execution time of the benchmark small, we need to reduce the simulation period as simulating a whole year would last more than one day. Thus, we reduce the total simulation period to eight weeks, using two characteristic weeks in winter, spring, summer and autumn, respectively. The characteristics of the eight weeks are high fluctuations in temperature, solar radiation and wind velocity. The start and end temperature, solar radiation and wind velocity of each week is adjusted so that the resulting weather profile is continuous. Figure 4 shows the resulting temperature profile.

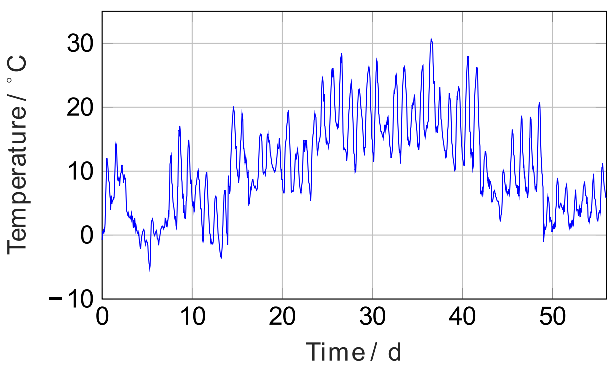

Figure 4. Outdoor temperature profile for the simulation period

2.7 Evaluation Criteria

The evaluation criteria are a basic part of the benchmark. To rate a control strategy, the benchmark model calculates the frequently used criteria comfort, energy consumption and energy costs.

The control of a building aims to provide a certain comfort to the user. Thus, the comfort is a key factor in building control strategies that we include in the benchmark. To rate the thermal comfort, Fanger [28] defined the predictive mean vote (PMV), which divides the comfort level into seven groups (hot, warm, slightly warm, neutral, slightly cool, cool, cold). Since each person's sense of comfort is different, the predicted percentage dissatisfied (PPD) shows a statistical distribution of the PMV. To rate the thermal comfort, the benchmark calculates the PMV and PPD.

Furthermore, the benchmark calculates the total final energy. The final energy consumption includes the gas and the electricity from the grid. The power fed into the grid is calculated as a negative energy purchase.

Besides the energy consumption, the energy costs for operating a building are vitally important; a highly energy efficient control strategy will rarely be implemented if it leads to uneconomical high costs. Thus, the benchmark needs to consider the operating costs of the energy system.

The energy system of the benchmark building uses electricity and gas. We define the price based on the electricity and gas market in Germany. According to a pricing list of the energy provider Werl [29], we split the electrical tariff into a high-rate tariff and a night tariff. The high-rate tariff is 29 ct/kWh and active between 6:00 am and 10:00 pm. The night rate is 19 ct/kWh. The two different tariffs enable a more cost-efficient operation by producing and storing heat and cold at night.

According to [30], the produced electricity of the CHP can be sold at a price of 12.34 ct/kWh. If the produced electricity is consumed by the building, a surcharge of 4 ct will be paid. The selling price of the produced electricity of the photovoltaic system is set to 10.5 ct/kWh. Based on [31], we assume a gas price of 6.09 ct/kWh.

3 Results and Discussion

We implemented the developed building and its energy system in the modeling language Modelica [32]. Modelica is an object orientated language and thus is suitable for modeling complex energy systems. The benchmark model is published in the open source library AixLib [33]. To simulate the benchmark model, we used the software Dymola.

3.1 Benchmarked Control Strategies

We apply the benchmark to two different control strategies to evaluate the meaningfulness of the benchmark. The control strategies are not optimized to be particularly energy or cost efficient. They should rather demonstrate the benchmark and serve as a first reference.

The first control that we apply to the benchmark is a basic control. The basic control has a heating and cooling mode with a fixed set-point temperature for the ventilation units and the concrete core activation. The mixing and throttling valves in the ventilation units and in the concrete core activation (CCA) are controlled by PID-controllers. All heat and cold generators have fixed flow temperature set points. Additionally, two-point controllers switch the heat pump, boiler and CHP on and off depending on the storage temperatures. The air-handling unit and all pumps operate at nominal power.

The second control is a night tariff control. It aims to decrease the electricity costs. The heat pump operates only at night trying to load the heat and cold storage. Additionally, the air-handling unit is switched off at night (between 10 pm and 6 am) to further reduce the electricity consumption. All other components are controlled in the same way as in the basic control.

3.2 Results

Figure 5 shows the total energy consumption and the operation cost for the two benchmarked control strategies. Further, Figure 5 shows the mean PPD and absolute mean PMV values. The mean PPD and PMV values do not allow a detailed analysis of the comfort. Nevertheless, the mean values represent the comfort level in general. Smaller values for the PPD, PMV as well as the energy consumption and operational costs indicate a better control of the benchmark building.

The basic control consumes 3.7 GJ energy and produces 16800 € costs. The thermal comfort reaches a high level with a mean PPD of 6.3 % and an absolute mean PMV value of 0.25.

In contrast, the night rate control saves around 42 % energy (2.16 GJ) and 46 % (9100 €) of the operational costs. However, the thermal comfort decreases in comparison to the basic control. This is caused by using the heat pump only at night. The heat pump is not always able to charge the cold storage at night. This leads to higher room temperatures in periods with high internal gains caused by high outdoor temperatures and solar radiation. Therefore, the thermal comfort is smaller for the night rate control than for the basic control.

The results show that the developed benchmark provides a standardized evaluation of control strategies. The complexity of the designed energy systems provides a wide range of different control options leading to different energy consumption, costs and thermal comfort.

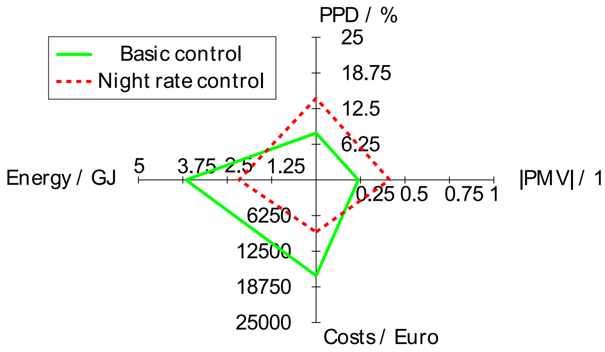

Figure 5. Results of the two benchmarked control strategies

Thus, the benchmark model is able to figure out the potentials of efficient and performant control strategies. In our example, the basic control reaches higher thermal comfort but less energy efficiency compared to the night rate control. However, figuring out which control performs better in total depends on the prioritization: a building operator would prefer the night rate control whereas occupants would prefer the basic control.

A disadvantage of the benchmark model is its complexity caused by the high number of actuators, which leads to a high effort to apply a control strategy.

Further, a benchmark holds the risk of overfitting. A control strategy could be tailored to the benchmark so that it only achieves good results in this benchmark. Applied to other systems, such a control could lead to low control performance. To avoid this problem, we suggest developing a bunch of different building models as standardized benchmark systems.

Furthermore, benchmarking control strategies based on standardized building models leads to comparable results. With a growing number of applied control strategies, the benchmark could become more and more useful.

4 Conclusion

In this paper, we presented a simulation-based benchmark model to rate the performance of different controllers and control strategies in the building energy domain. The core of the benchmark is a specially designed office building. The building consists of five representative rooms and an energy system with various heat and cold producers. The complexity of the system offers a high range of operating modes. Thus, the energy system sets a challenging task to the controller. Therefore, the benchmark is able to investigate the potential of advanced and efficient control strategies in comparison to other control strategies.

We applied the benchmark to two simple control strategies in order to evaluate the usefulness of the developed benchmark system. The first control strategy is a simple mode-based control in combination with PID control. The second control strategy extends the first one by exploiting a night rate. The benchmark model calculates higher costs and energy consumption for the basic control in comparison to the night rate based control. By contrast, the average comfort is higher in the basic control. As a conclusion, the benchmark is able to point out strengths and weaknesses of the tested control strategies.

Further work aims to improve the evaluation criteria. Besides, the energy consumption, costs and thermal comfort, the carbon emissions as well as the electricity consumption of the control algorithm itself could be considered. Additionally, a standardized criterion that combines all other criteria in one value could facilitate the rating of different control strategies.

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