The role of HVAC controls in building Digital Twins: lessons learned from demonstration buildings with an application to air handling units

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Abstract

This study investigates how information about the controls of heating, ventilation and air-conditioning (HVAC) systems can be gathered from building automation systems for the creation of Digital Twins in Building Performance Simulation (BPS). The concept of Digital Twins in BPS environments is commonly used for Fault Detection and Diagnosis or performance gap analysis during operation. In the creation, often emphasis is put on building physics or user behavior. In modern buildings, automation systems play an important role to guarantee user comfort requirements as well as an energy efficient operation. To replicate the behavior of real HVAC systems in Building Performance Simulations, the underlying control logic has to be known. To gather this information in operation we have investigated three sources: firstly, documentation from the design phase including already existing simulation models, secondly, the control code on automation systems and thirdly, reverse engineering from measured data. The study focuses on air handling units and is based on experiences in state-of-the-art building demonstrators from research projects in Sweden and Germany.

Key innovations

• Three options for the information transfer of control programs from the building automation domain into Building Performance Simulations are identified and described. This connection is necessary to promote the penetration and usefulness of Building Performance Simulations as Digital Twins in planning and for Fault Detection and Diagnosis in operation.

• Using project examples, we empirically demonstrate the feasibility and current barriers of the three options.

• We provide a clear description of the necessary steps for a seamless automated connection between building automation systems and Building Performance Simulation environments.

Practical implications

The presented methods and results tackle the performance gap of heating, ventilation and air-conditioning (HVAC) systems in existing and new buildings related to control issues. The use of Digital Twins, which particularly mirror the control of HVAC systems, has a high potential to close this performance gap and thus contribute to a climate-neutral and decarbonized building operation. However, the detailed modeling of controls is a blind spot of many of today’s Building Performance Simulation applications. Our study therefore addresses academic and professional developers and users of Building Performance Simulations and building automation system to establish a closer link between their domains.

Introduction

To meet user’s comfort requirements and ensure an energy efficient operation of heating, ventilation and air-conditioning (HVAC) systems, today’s commercial buildings are increasingly equipped with building automation system (BAS). The implemented control strategy has a large impact on the energy performance (Fernandez et al. (2017)). In recent years tools for Fault Detection and Diagnosis (FDD) in operation have been developed and implemented in practical applications using the concept of Digital Twins (DT) (Hosamo et al. (2022), Xie et al. (2023)). Among data driven approaches white-box models in Building Performance Simulations (BPS) allow for a detailed modeling of the underlying physics and are thus a powerful tool for Digital Twins (Ruepp et al. (2022)).

BPS models have to be fed with various inputs ranging from climate data and material properties to occupant behavior which are typically estimated from measurements, data-sheets or average values. To replicate the controls of HVAC systems, detailed knowledge about the underlying control logic is needed. This includes setpoint values, measurements as inputs, the control topology with their connection and processing and the connection of outputs to actuators. Standardizing and digitalizing this information is still a work in progress (Ihlenburg et al. (2020)).

The present study investigates approaches how to gather this information for the creation of Digital Twins (see Figure 1). The first approach consists in extracting information from design documents. Moreover, if simulations were used to support the design phase, existing BPS models can be updated and continue to be used. The second approach is to reproduce the control logic implemented on BAS which requires that this control logic is accessible and readable. Third, reverse engineering approaches, where measured values are used to infer the likely implemented control logic, are possible. Each approach has its technological and organizational barriers which are out-
lined in this study.

The study focuses on air handling units (AHUs) which are commonly used in different building types and often a source of malfunction (Gunay et al. (2017)). Thus, an accurate modeling of the controls is needed for a reliable Digital Twin. To showcase different approaches, AHUs in state-of-the-art case study buildings from research projects in Germany and Sweden are used. A factory building, an office building, a lecture building and a student residence have been selected. This selection represents a wide range of buildings with high user requirements for indoor thermal comfort and energy performance. The complexity of the AHUs in the demonstration objects varies but the buildings have in common that the control strategy for the AHUs has a relevant impact on the overall energy performance as well as the indoor climate.

The remainder of this paper is organized as followed: first, the different approaches for the information collection for HVAC controls are described. Then, the results and findings in the case study buildings are presented for each of the previously introduced approaches. In the final discussion a focus is on the energy requirements and the penetration of BPS as a driving force for Digital Twins.

Methods

Planning documents & simulations

The implemented operation of HVAC systems should be defined by HVAC and automation engineers in the planning phase (see left part in Figure 1) based on user’s and operator’s requirements. The documents issued from the design phase should unambiguously describe the intended control concept. Since the preparation takes place before the tender is awarded, they are still independent of manufacturer specifications. According to international and national standards such as ISO 16484-3 (International Organization for Standardization (2005)) and VDI 3814-4-3:2022 (Verein Deutscher Ingenieure (2022)) planning services for building automation and control systems should include 1. automation schemes, 2. functional lists and 3. a textual functional description. Automation schemes (see Figure 2) should contain a scheme with the physical system and sensors, a function structure with other inputs such as set points and their processing and characteristic curves to unambiguously describe the intended control. Typical challenges are adaptations during the construction and operation phase that cause the actual operation to deviate from the intended one.

In addition to this normative planning output, simulation models might be available from the planning phase when they were used to support architectural or engineering design decisions. Depending on the tools used, the degree of detail and their availability, information about the intended control can be taken from such models directly.

Control code implemented on automation systems

The actual operation of HVAC systems is defined by the implemented control code (see middle part in Figure 1). This control code is typically implemented on the automation or field layer of the present automation architecture while set points are often defined on the management layer (see Figure 3). While simple actuators, such as valves, typically do not have an integrated controller and receive a control signal from the automation level, intelligent subsystems might just get an activation signal and a setpoint and control inner components with integrated controls. An example for such systems are heat pumps, where often a set point for the water supply temperature is given by a superior control instance. The heat pump’s internal logic then controls the targeted water supply temperature.

To reproduce the control logic in a simulation environment, first, the control code has to be accessible and not hidden in proprietary systems. Second, engineers capable to read and understand the implemented code are needed. In general many approaches and standards exist on the building automation market for different automation tasks (Mishra and Wen (2018); Domingues et al. (2016); Royapo et al. (2018); Waide et al. (2014)) including emerging trends towards autonomous subsystems, cloud infrastructures, Industry 4.0 etc.
Reverse engineering from measured data and building management systems

If no information about the implemented control strategy is available from the design phase or the automation systems the control has to be reverse engineered from measured data. The level of detail which can be deduced depends a) on the measurement infrastructure and b) the complexity of the air handling unit. Together with typical control approaches from literature (e.g. Siemens Schweiz AG (2019)) a possible control can then be estimated. For a connection of the control in a Digital Twin, measured values as well as setpoints are required. This information must be connected to the simulation model in real time or as stored time series.

Results and findings in case study buildings

Wilopark

A factory building and an administrative building in Dortmund (Germany) were investigated as part of the research project VEProB. The buildings are in operation since 2020. The two buildings have 46 air handling units ranging from simple extract units to units including humidifying, dehumidifying and variable air flows. The buildings and their HVAC systems are operated directly by the building owner. For this study an AHU with a liquid heat exchanger, a mixing box, a heating and cooling coil is evaluated (cf. Figure 4).

Planning documents From the design phase documents according to VDI 3814-4.3 (Verein Deutscher Ingenieure (2022)) are available. However, since the function structure and characteristic curves are missing in the control schemes they are not fulfilling the requirements of the standard. Moreover, the documented configuration of the AHU does not match the built system due to late changes. Instead of the built configuration depicted in Figure 4, the documents states a sequence with heating coil, supply air fan, cooling coil and steam evaporator in the supply air duct.

The control concept is described as follows:

“The supply air temperature is controlled depending on the room temperature. The continuous controller compares the room temperature measured by the sensor with the setpoint. If there is a deviation, the controller causes the heating or cooling valve to be adjusted. […] A supply air temperature minimum limit ensures that the supply air cannot be blown in so cold that uncomfortable drafts occur [...]. The supply air may be blown in at a maximum of 2 K (freely parameterizable) below the room temperature. The room ventilation must be controlled according to the humidity in the room. If this value is exceeded, the supply air volume flow is increased up to the max. value.”

In some of the AHUs with a similar control approach the control has been switched to a constant supply air temperature, the defined undertemperature of 2 K has been set to 5 K in operation and other setpoints such as the target room temperature differ in operation, too. Additionally, the description does not contain information about the sequence in which the heat exchanger, the mixing box and the heating and cooling coils should be used and does not refer to explicit measurements or data points. In general, the intended control logic can not be replicated. Information regarding data points to be saved and sampling intervals is missing.

Simulations During the design phase BPS have been carried out using the software TAS" by an external service provider. The simulation focused on the calculation of load profiles for heat, cold and electricity. System simulations have been carried for the heat and cold supply system using the software component TAS systems. In general, since TAS uses an hourly time step and does not allow for a coupled simulation of buildings, HVAC system and their control these simulations have limited reliability when it comes to control design. The service provider has refused to provide the simulation models, so they are not available for later use.

Control code The majority of the AHUs is controlled by programmable logic controllers (PLCs) which are programmed in the integrated development environment (IDE) "e!cockpit". In the research project VEProB access to the software and the automation programs is available from the design phase or the automation systems. Therefore, the intended control logic can not be replicated.

provided through the building operator as project partner. The software allows for programming using five languages Instruction List (IL), Ladder Diagram (LD), Function Block Diagram (FBD), Sequential Flow Chart (SFC) and Structured Text (ST) according to IEC 61131-3. The programming has been written in ST based on the previously described planning documents by a building automation contractor outside of the research project.

From the control code the implemented control strategy can be deduced as follows (cf. Figure 4): the measured extract temperature is compared with the setpoint. Taking into account other inputs such as upper and lower supply air temperature boundaries, the cascade controller $\text{Casc}$ calculates a target supply air temperature. Subsequently, the sequence controller $\text{Seq}$ compare the target value with the actual supply air temperature and calculates an output signal between 0 and 100 % with 50 % as neutral position. This output signal is the input for the function blocks $\text{SecH}$, $\text{SecC}$, $\text{SecMix}$ and $\text{SecHx}$. They are sequences for the heat exchanger, the mixing box and the heating and cooling coil.

The control blocks $\text{Casc}$, $\text{Sec}$, $\text{SecH}$, $\text{SecC}$, $\text{SecMix}$ and $\text{SecHx}$ in Figure 4 are taken from a manufacturer-specific library. Their functionality and their in- and outputs are described in a manual, however, the underlying code is not available. The expected control characteristic of such blocks has to be replicated in simulation which is a clear limitation for a unambiguous transfer. In this context it is also problematic, that inputs such as set values were often not available as time series in the monitoring database and thus not available as inputs in the simulation model.

Based on the control code a simulation model in IDA ICE 5.0 has been created. To focus on the characteristics of the AHU and its control the building has not been modeled and the room temperature $t_{\text{extr}}$ and humidity have been used as input for the simulation. On the supply air side the measured temperature after the heating coil $t_{\text{mix,lvg}}$ is used as an input in simulation. This step is needed because, first, the exact performance of the coils of the liquid heat recovery unit are not available from the manufacturer. During the observed period the mixing box has been closed manually. Second, to exclude the influence of leakage through the flaps of the mixing box which have been closed manually during the observed period. The measured supply and return air flows have been used as inputs, too.

Figure 5 shows the time series of measured and simulated temperatures and thermal power for three days. The setpoint for the extract temperature (green dashed line) has been set on the building management system (BMS) to 20 °C. The supply air is varied such that the extract temperature (green dashed line) has been set on the building management system (BMS) to 20 °C. The supply air is varied such that the extract temperature rises more slowly which can be, first, due to different inertia in the simulated and real system but also to different controller parameters.

The measured supply air temperature $t_{\text{sup,meas}}$ reaches values from calibrated heat meters. The previously described differences in the supply air temperature result in significant deviations of the thermal power of the heating coil. The measured supply air temperature $t_{\text{sup,meas}}$ reaches values from calibrated heat meters. The previously described differences in the supply air temperature result in significant deviations of the thermal power of the heating coil. The measured supply air temperature rises more slowly which can be, first, due to different inertia in the simulated and real system but also to different controller parameters.

The simulated heating power is compared with measured values from calibrated heat meters. The previously described differences in the supply air temperature result in significant deviations of the thermal power of the heating coil. The measured supply air temperature $t_{\text{sup,meas}}$ reaches values from calibrated heat meters. The previously described differences in the supply air temperature result in significant deviations of the thermal power of the heating coil. The measured supply air temperature rises more slowly which can be, first, due to different inertia in the simulated and real system but also to different controller parameters.

A comparable situation can be found for the cooling supply: The cooling supply is composed by three compres-

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3https://equa.se/en/
Through the research project the design phase no documented planning documents are available, the relevant information about the controls of AHUs have been gathered mainly from design documents and reverse engineering from measured data (Walther and Voss (2022)).

Reverse engineering Through the research project the buildings and AHUs are largely equipped with sensors. This measurement infrastructure allows for a detailed evaluation of the system operation, however, measurements between the heat recovery and the mixing box are missing. Assuming that no design documents or control code were available, it can be observed from measured data that the extract air temperature is the controlled value etc. (see upper diagram in Figure 5). Together with expert knowledge and approaches from literature the control scheme such as depicted in Figure 4 could be reproduced. In a previous study for a different AHU with no available control code, the relevant information about the controls of AHUs have been gathered mainly from design documents and reverse engineering from measured data (Walther and Voss (2022)).

Testbed Akademiska hus

The Testbed Akademiska hus is part of the live-in lab on the KTH campus in Stockholm (Sweden). It is used as lecture building with student work places. The building has two identical air handling units which are operated in parallel (see Figure 6). The air handling units have a rotary heat recovery system, a heating and a cooling coil.

Planning documents The automation schemes from the planning phase include the sensors and actuators but do neither include characteristic curves nor the function structure according to ISO 16484-3:2005 (cf. Figure 2). Moreover, the supply air fan in the built system is in a different position than in the drawings (see Figure 6). The concept for heating and cooling the control is textually described as follows:

“*The temperature sensor GT101 controls the speed control device RC601 and the control valves SV401 and SV201 in sequence so that the calculated value is obtained. Control sequence from maximum cooling: Control valve SV401 is controlled for cooling 100-0%. The speed control device RC601 is controlled for heat recovery 0-100%. Control valve SV201 is controlled for heating 0-100%.*”

The setpoint value for the supply air temperature is given depending on the ambient temperature. According to the building operator the design documents are frequently used and helpful to understand the operation of the air handling units.

Simulations BPS have been carried out in the design phase using IDA ICE. For this study simulation models were not available yet.

Control code The air handling units are controlled by a PLC which is programmed according to IEC 61131-3 in the FX-editor⁴. For this study the control code was not available.

Reverse engineering The design documents include lists about the data points which are logged in a database. These lists include the set points as well as the measurements. Since all relevant set points and measurements are available and, with a heat exchanger, a heating and a cooling coil, the AHU is relatively simple, the implemented control logic can be reverse engineered relatively easily.

Testbed EM and Testbed KTH

The Testbed EM has three buildings and is also part of the Live-In Lab on the KTH campus in Stockholm (Sweden). The buildings are used as student apartments. The Testbed KTH is located in one of the buildings and has separated rooms and HVAC systems and controls. The fresh air supply is provided by AHUs which have a pre-heating and pre-cooling coil connected to a borehole field, a heat exchanger, a heating and a cooling coil (see Figure 7). The supply air of each AHU is split up into multiple ducts. Each of these ducts has another separate heating coil and provides air to a group of apartments.

Planning documents From the design phase no documents about controls of the AHUs are available.

Simulations During the design phase BPS have been carried out by an external service provider using IDA ICE.

¹https://support.fidelix.com/en/knowledge/fxeditor

Figure 6: Simplified scheme of AHU and controls deduced from textual description in Testbed Akademiska Hus.

Figure 7: Simplified scheme of AHU and controls in Testbed EM/KTH deduced from BPS from design phase.
The AHUs and their control have been adopted individually and not just taken from the component library. The control has been created using graphical function blocks. In the simulation the supply air temperature per AHU is calculated from a via a P-controller with 1-K proportional band (see Figure 7). The controlled value is the extract temperature of all connected flats. The heating coils in the supply air ducts are controlled by a P-controller, too.

**Control code** In the Testbed EM the AHUs are controlled by a PLC while in the Testbed KTH they are controlled via a BACnet building controller. The control code has not been accessible for this study.

**Reverse engineering** In a previous study, the calibration of a simulation model for parameters of building physics, building services and use was carried out (Molinari and Rolando (2020)). The uncalibrated model, for which the control concept of the AHUs has been reverse engineered based on measured data, shows a Coefficient of Variation (Root Mean Square Error) of 46 %, which illustrates the order of magnitude of possible deviations.

**Discussion** The results from the case study buildings are compared in this section and collected in Table 1. Each column represents a case study building and each row an approach for the information collection of controls. For each approach different sub-categories are assessed.

The results show a mixed picture: The available planning documents (Pd) generally do not fulfill the expectations from ISO 16484-3 and do not include control diagrams (Dia) or control schemes (Sc). Hardware configuration and setpoints often differ between design intention and the built system. Despite the gaps, the textual description (Td) for Testbed Akademiska hus is very meaningful and informative. This is underlined by the frequent consultation through the building operator.

Simulations in the design phase (SiD) have been carried out (done) in all projects. For this study only the simulation model for Testbed EM/KTH is available (Av). It also includes a detailed simulation of controls (Ctrl).

The accessibility of control code (Cc) is best in the Wilopark case study. The fact that the building operator as main stakeholder for the building operation has access to the implemented control code is a clear advantage. The delivery of the control code to building operators should be regulated by contract. A further challenge are libraries (Lib) of function blocks where the underlying control code is not accessible.

For reverse engineering approaches (Re) with some exceptions the AHUs are generally equipped with enough measurements (Meas) allowing for a detailed understanding of the system behavior. However, only the in case of Testbed Akademiska hus a relatively simple standard configuration (Std) is used which allows for a replication of controls.

Based on these findings the following conclusions can be made: On the one hand, due to the lacking information in planning documents and the discrepancies between the designed and built systems, planning documents are rather unsuitable for the time- and cost-efficient creation of a useful Digital Twin.

Reverse engineering of the control concept from measured data seems to be the most cumbersome and intricate. First, sensors have to be present in the relevant positions, second, the data has to be available (no data shortage) and measurement tolerances have to be considered. Additionally, in practice, the naming of data points in databases often is ambiguous and unclear. Finally, setpoints have to be logged in a database, otherwise fundamental information is missing. For the investigated AHUs, although the data are available, deep expert knowledge for various systems is needed to identify the underlying controls.

Among the three presented approaches the replication of control code from automation systems into a simulation environment as described for the Wilopark is the most seamless approach for the creation of a Digital Twin. The transfer of control code is the most promising towards an automated work flow e.g. via the xml-file defined in IEC 61131-10 for PLC based systems. However, closed manufacturer specific libraries and controls are a barrier.

From an operation perspective, the most straightforward way for creating a Digital Twin is taking the one which is already existing from the design phase. Figure 8 depicts an ideal work flow where building simulations are part of the design process and as a result the control program is transferred in the BAS. The existing building and HVAC models can then be used for performance gap analysis and FDD in operation. The information transfer can be done by one-time transfer of a file exchange format. In this context, the OpenBuildingControl project is an important contribution (Wetter et al. (2022)). Another possibility is the further use of the controller in the simulation environment by coupling it to sensors and actuators of the real plant in real time, e.g. via the OPC Unified Architecture (OPC UA) standard.

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<th>Testbed EM/KTH</th>
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Table 1: Summary of results. Pd: Planning documents (Dia: Control diagrams, Sc: Control schemes, Str: Control structure, Td: Textual description), SiD: Simulation in design (Done: Simulations carried out, Av: Available, Ctrl: Including control simulation), Cc: Control code (Av: Available, Lib: Open libraries), Re: Reverse engineering (Meas: Enough measurements available, Std: Standard AHU)
Influence of simulation requirements

In all projects BPS have been used during the design phase but their quality and availability differ a lot. While for the Wilopark the existing simulation models were not handed over and the software used is not suitable for HVAC and controls simulation they were available for Testbed EM/KTH including control simulation. One could hypothesize that while in Germany simulation services are rare and thus rather exclusive knowledge they are a standard service in Sweden.

Why are simulations so much more common in Sweden and does that increase the quality of available information about controls? On the one hand, the German building energy law GEG (Deutscher Bundestag (2020)) requires that the planned building’s primary energy consumption is below those of a reference building of identical shape with predefined physical properties and HVAC systems. The calculation is carried out on a monthly basis according to DIN V 18599 (Deutsches Institut für Normung (2018)). Simulations are a commonly used tool for various tasks but are not mandatory.

On the other hand, Sweden has introduced the requirement that “Verification that a building meets the requirements of primary energy number [...] should be done based on measurement in the finished building.” (Swedish National Board of Housing, Building and Planning Boverket (2019)). While for residential buildings monthly calculations are possible, simulations with time steps shorter than one hour are required for non-residential buildings.

Conclusion

Our study has identified three methods to gather information about controls of HVAC systems and evaluated them in case study buildings. The bidirectional information and knowledge transfer between building automation systems and Building Performance Simulations remains a challenging task. While the quality of the design output falls short of expectations, the transfer of code from controllers seems to be the most promising towards an automated processes. To leverage the full potential of Digital Twins in white box models, Building Performance Simulations should be part of the design phase, updated if necessary and a control instance in operation. The exemplary comparison of simulated and measured performance of an AHU has shown that more emphasis has to be placed on the parametrization of controllers.

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