Digital Twin with Multi-Input and Multi-Output optimisation for Air-Conditioning Systems

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ABSTRACT: Within this paper, a modular and scalable energy inspection method for performance analysis and Fault-Detection and Diagnostics (FDD) of air conditioning systems is presented. The significant innovation aspect is the guarantee of a high degree of automation through the exploitation of operating data with model-based analysis. To detect deviations from the ideal operating condition and initiate optimisation measures automatically numerical methods are deployed in combination with the building automation system (BAS). The generic approach opens access to the use of data-driven commissioning, maintenance, and repair strategies.

1. INTRODUCTION

The topics of digital construction and operations increasingly present new challenges to all project stakeholders in the construction industry. Due to the rapid development of digital communications and collaborative work, construction processes are being realigned to guarantee a continuous and loss-free data exchange between all trades involved. This aims to prevent errors and improve productivity along the entire value-added chain and consequently over the entire life cycle of a building. The working methods used for this are known as Building Information Modelling (BIM). In the USA and Northern Europe, BIM is widely used and highly valued in small and large construction projects. In the case of Austria, the development of BIM know-how is also well advanced, but more and more in large construction enterprises. However, small and medium-sized enterprises (SMEs) still require know-how to bridge the gap. Also, current development work is centred on the planning and construction process. Information requirements to ensure efficient operation are hardly considered. There is also a lack of digital tools to support commissioning management employing technical monitoring. Especially the extended use of BIM through the structured combination with an operational data twin allows the provision of efficient use of resources of building services installations and systems.

To sidestep these performance gaps, digital building models (BIM models) will in future have to be provided with a uniform identification and a definition of characteristics - already in the planning phase. Through the identification, objects can be represented clearly in the model, and by standardising features (attributes), which of these can be used across all trades, e.g. in technical building management and building automation. The creation and assignment of uniform identification systems and unambiguous feature definitions, which form the basis for further use of the BIM model in the operation and utilisation phase, is of particular importance. Only in this way is it possible to link the domain-specific information with the operational data and create the essential prerequisite for automated system optimisation during commissioning and throughout the entire life cycle. This also enables added value to be gained from the already existing building automation.

This paper presents a viable concept for a modular and scalable energy inspection employing automated operational performance analysis and Fault-Detection and Diagnostics (FDD) for an air-conditioning system. The major innovative leap forward in this context is the assurance of a high degree of automation through the targeted use of operating data and multi-input multi-output (MIMO) optimisation analysis. Numerical methods are used in combination with building automation (BA) to independently detect deviations from the ideal operating condition at facility and system-level and to be able to initiate optimisation and inspection measures automatically (autonomous analysis operations). The generally acceptable approach hence achieved open access to the use of data-driven commissioning, maintenance, and repair strategies.

2. DEVELOPMENT OF THE DIGITAL TWIN

2.1 TEST FACILITY AND DEVELOPMENT ENVIRONMENT

An existing air-conditioning system was used for the development and validation of the digital twin with the MIMO-optimisation algorithm. The plant was designed for an air volume flow rate of 4300 m^3/h and has a steam humidifier, a cooling coil, and a preheating and post-heating coil and an energy recovery system based on a regenerative enthalpy exchanger (see. Fig. 2.1). The cooling and heating supply is provided by a reversible heat pump and/or warm and cold water tank. The fans are designed as EC motors so that infinitely variable operation up to 20 % of the nominal volume flow rate is possible.

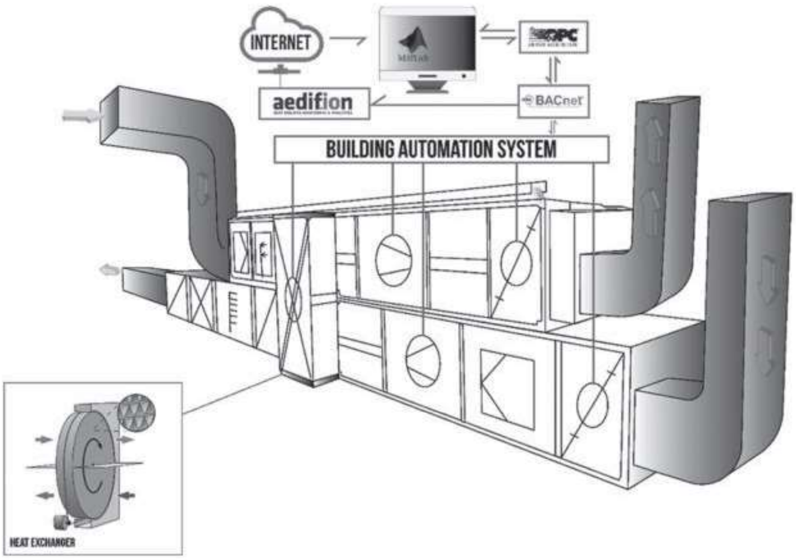

Fig. 2.1: Schematic diagram of the full air-conditioning system under investigation

The air is distributed to the individual ventilation zones via distribution pipes. Independently variable volume flow rate controllers provide the supply of the desired air volume flow rate for each zone. The sensors already available were supplemented by temperature and humidity sensors in the fresh air duct and energy meters for the heating and cooling coils. In this way, the data basis for a (quasi-stationary) energy balance of the system could be achieved without significant additional financial outlay.

2.2 DATA ACQUISITION AND DATA SUPPLY

The data was provided entirety via the building automation system. For this purpose, the sensor data were transferred to the Building Automation Communication Network (BACnet) via gateways and stored in a cloud platform via an edge device (See. Fig. 2.2).

The proposed configuration offers data from the air conditioning system and the entire building automation system. This made additional data (room air temperature, CO_2 concentrations, setpoint temperatures, valve positions, etc.) from sub-systems available so that all relevant data can be centrally stored and easily included in the analysis procedure. The combination of the operating data with the system-defined ontology and semantics opens up new approaches for energy demand analysis and optimisation.

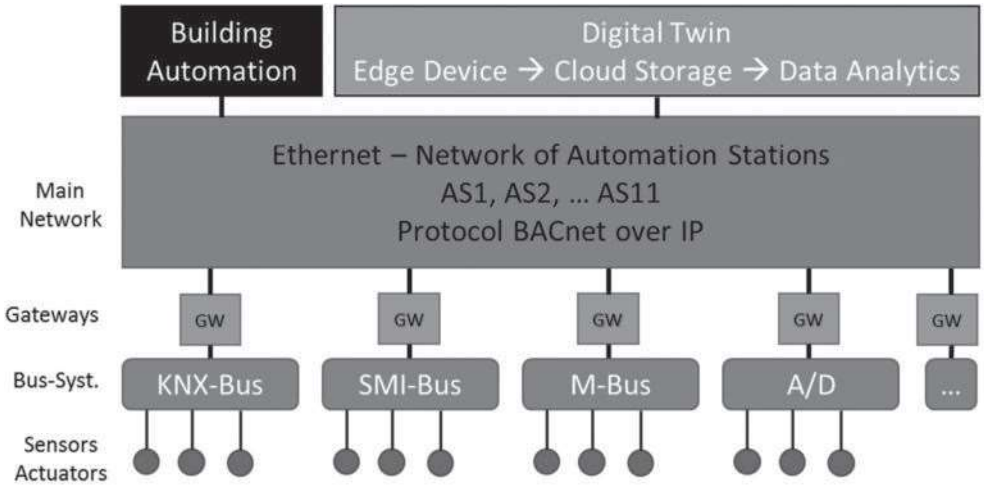

Fig. 2.2: Scheme of the digital twin integration

2.3 DEVELOPMENT OF THE MIMO-OPTIMISATION

Within the building technology service sector, the national implementation of the European decarbonisation strategy is considerably influenced by the EPBD guidelines. For example, the legally required energy inspection of heating and air conditioning systems was implemented by the EU Directive 2010/31. Similar innovations are expected, e.g. pertaining to the automated energy inspection and the introduction of the Smart Readiness Indicator (SRI) by the EU Directive 2018/844. Besides, continuous further development of the normatively defined energy performance of buildings (e.g. EN 16798-5-1) is recognisable. In particular, the normative developments enable the provision of system-specific information such as partial load efficiencies of heat recovery systems. This information can, therefore, also be presented as a basis for model-based analysis. A prerequisite for this, however, is that the client information requirements (CIR) contained in corresponding performance specifications already in the planning phase.

If such information is provided, a thermodynamic model of the air-conditioning system can be derived. With the model, the change of state due to the heat recovery system, cooling and heating coils and the humidifier can be determined. The boundary conditions can be directly assigned based on the given inputs such as weather conditions and the thermal comfort constraints. The minimum energy effort can be computed based on the minimisation of the energy consumption of all relevant devices (heating and cooling coil, humidifier, etc.). This can be achieved by applying a multi-input multi-output optimisation algorithm. To achieve the best possible scalability of the analysis algorithm, a gradient-based optimisation solver for non-linear objective and constraint functions was used. Information from the BIM model can therefore be linked and created without additional manual effort for the matrix derivation. The implementation of the proposed MIMO-optimisation approach is shown in Fig. 2.3.

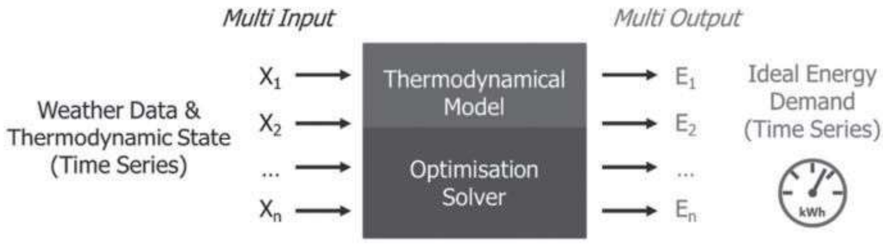

Fig. 2.3: Scheme of the used MIMO-optimisation approach during the data analytic procedure

3. RESULTS

3.1 ANALYSIS OF THE ACTUAL STATE

The EPBD standards facilitate the international harmonisation of the methodology for the assessment of the energy performance of buildings. In this context, the EN 16798-1 specifies the requirements for air-conditioning systems regarding the indoor environmental parameters such as thermal comfort, indoor air quality, acoustics etc. The standard includes designing criteria based on physical quantities, occupancy schedules and energy demand calculation methods. Also, the EN 16798-5-1 includes appropriate BIM parameter requirements to compute the efficiency of heat recovery systems under full and partial load conditions. Due to these parameters, the energy consumption of the entire air-conditioning system can be determined based on thermodynamical principles and compared with the actual energy demand. Fig. 3.1 shows the measured and calculated results based on the digital twin data of an existing air-conditioning system for one year. The comparison shows a good correlation between the experimental data and computation results. Hence, the outlined method appears to be eligible for forecasting and evaluating the energy demand for air conditioning systems.

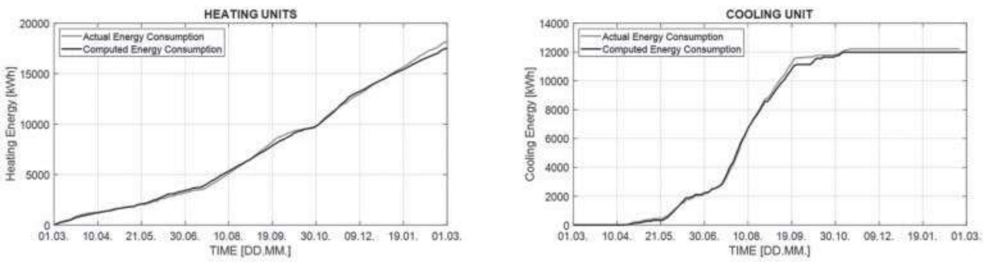

Fig. 3.1: Model validation results for heating coils (left) and cooling coil (right)

Additionally, the EN 16798-1 offers standardised categories to classify the building system design. For the determination of the ventilation rate, several methods are proposed. Besides the perceived air quality and predefined flow rate determination, methods using limit values of substance concentration can be applied. The latter design approach calculates the ventilation rates based on a mass balance formula for the concentration of the substance taking into account the outdoor concentration. In such a case, the CO_2 concentration can be used as a tracer of human occupancy and therefore enabling demand-controlled ventilation. Based on this, the energy demand for different indoor environmental qualities (IEQ) can be determined and compared. Fig. 3.2 shows the determined energy-saving potential of the heating (left diagram) and cooling units (right diagram) for different IEQ scenarios between March 2018 and February 2019.

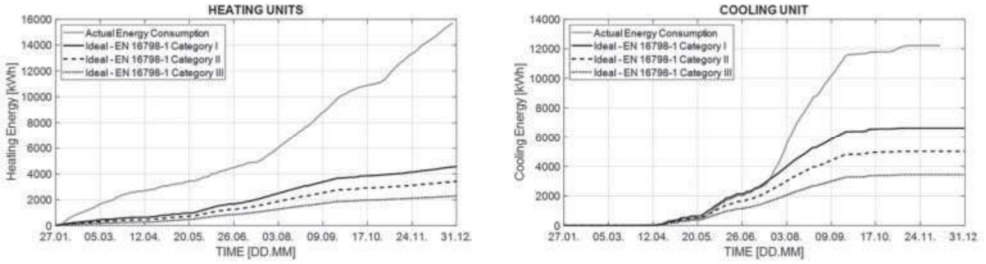

Fig. 3.2: Results of the energy consumption analysis for the heating and cooling units

For the heating units, the calculations predict a saving potential of 71 % for the category I variant, 78 % for the category II variant and 85 % category III variant. For the cooling case, 46 %, 59 % and 72 % were assessed for the investigated categories. An identical energy consumption analysis was also rendered for the steam humidifier. For the steam humidifier, a saving potential of 37 %, 63 % and 87 % have been calculated for the IEQ category I, II and III.

3.2 EVALUATION OF THE IMPROVEMENT MEASURES

Based on the energy-saving analysis control strategy, enhancements have been derived, and between July and October 2019, appropriate control adjustments applied. During this period, an IEQ category III was assigned. Thereafter, the energy consumption of the air-conditioning system was again analysed. In addition, an occupancy evaluation was carried out. The evaluation indicated high satisfaction regarding indoor air quality and thermal comfort.

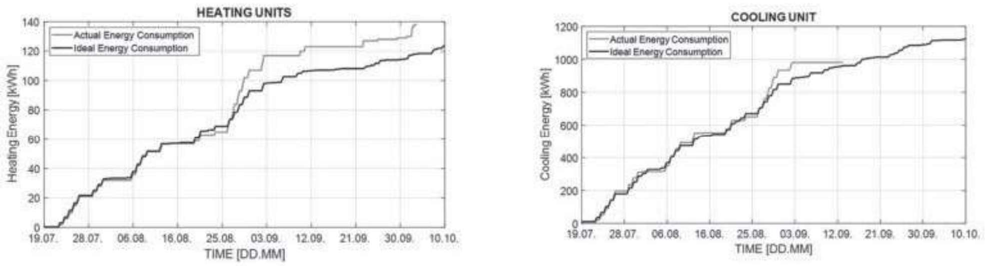

Fig. 3.3: Energy consumption comparison after control strategy adjustments

The impact of the adjustments to the actual energy consumption is illustrated in Fig. 3.3. The experimental results concur well with the expected ideal energy consumption of the heating and cooling unit. The same findings were achieved during the humidifier energy demand analysis. Accordingly, the proposed modular and scalable energy inspection method can facilitate the Fault-Detection and Diagnostics (FDD) analysis of air conditioning systems. The anomaly detection on building automation system-level can initiate optimisation and inspection measures automatically. Hence, the achieved results open access to the use of data-driven commissioning, maintenance, and repair strategies.

4. CONCLUSION AND SUMMARY

A model-based data analysis approach for energy demand inspection of air-conditioning systems was developed. In order to represent a reliable partial load behaviour and high scalability, the approach consists of several combinable submodels which are eligible to compute the thermodynamical state and energy consumption of the heat recovery system, humidifier, heating coil and cooling coil. To evaluate the performance gaps, the submodels were linked via constraint functions, and the ideal energy demands were identified by applying a MIMO optimisation approach. The proposed method permits to evaluate the actual performance of the air conditioning system against the ideal benchmark and to initiate countermeasures. Furthermore, the applied approach provides the necessary information requirements for BIM modelling so that the results could be exploited for future planning and optimisation operation of ventilation systems.

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