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Automated HVAC Control Creation Based on Building Information Modeling (BIM): Ventilation System

ANDREAS SPORR[1], GERHARD ZUCKER[1], (Senior Member, IEEE), AND RENÉ HOFMANN[1,2]
[1]Sustainable Thermal Energy Systems, Austrian Institute of Technology, 1210 Vienna, Austria
[2]Institute of Energy Systems and Thermodynamics, Technical University, 1060 Vienna, Austria

Corresponding author: Andreas Sporr (andreas.sporr@ait.ac.at)

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ABSTRACT Building Information Modeling (BIM) is a process that collects building data in a central data model. This data can not only be used to plan and construct a building but to design the controls for heating, ventilation and air conditioning (HVAC) systems. The relevant information about the building and its systems is used as the base for controller design, opening new opportunities like the automated testing and optimization of control strategies, both for energy efficiency and user comfort. This paper shows how the information in the BIM is used to design control strategies, including a completeness check and a resulting data set enhancement of this necessary information. It also shows a way, how a building, which is already operating, can be optimized using the operation data from energy systems to modify the existing controllers. The methodology is executed using a ventilation system that provides air quality by means of CO_2-driven control.

INDEX TERMS Automated control strategy development, building information modeling (BIM), controller optimization, HVAC control, industry foundation classes (IFC).

I. INTRODUCTION

When a building is planned by means of an integrated, digital approach, it is most commonly a process based on Building Information Modeling (BIM). A common model is used by architects, structural engineers, building services and other industries; all work contributes to the same data model (the BIM), filling it with data on the building envelope, the indoor design, the energy systems, the installed heating, ventilation and air conditioning (HVAC) components etc. and use this data to create a detailed model of the building. Based on this model, the planners can ensure a high level of planning quality, using automated model checks for clash detection (e. g. ducts that would run through walls without a matching wall opening) and to provide a viable model for simulations (e. g. to calculate the heating demand or analyse summerly overheating in critical zones). It is also used during construction to manage the progress and observe the costs of construction to maintain the given budget and determine the material amounts required at a given time.

Today, the core applications of BIM are planning and construction; building services are currently being standardized in Europe and facility management is also making amends to implement BIM for addressing the operation phase of a building. Making BIM planning data available in later building phases would be of great benefit for costs and quality during the life cycle. Lambrecht [1], state that the cost savings using BIM are up to 7%, considering only the planning phase. Extending the usage of BIM data towards commissioning and operation will further increase these benefits. This work takes a step in this direction and shows that the structured and consistent information, which is gathered in the BIM, is the foundation of controller design in building energy systems [2], [3].

Basically, this paper focuses on the work flow of an automation algorithm to create control strategies for ventilation systems only using data from BIM models. Controllers used within these strategies, are adjusted with well-known methods and their parameters are adapted within the updating process for improving the baseline control strategy. So called control strategies consist of a set of control blocks. With

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these blocks a building is controlled on two levels: automation level (activation time of the system, time schedules, etc.) and process level (mostly PID controllers or On–Off controllers). Thereby, a control block is a function with inputs, configuration parameters, and outputs.

This paper shows a workflow for the automatic design of control strategies for building energy systems. It focuses specifically on indoor air quality by means of CO_2-based control of a ventilation system and uses BIM model and additional data sources (e.g. national regulations and standards regarding indoor air quality) to gather the relevant information needed to design a control strategy. After this strategy is committed, it can be further optimized using the operation data of the ventilation system and on indoor air comfort to avoid peaks in CO_2 levels or on counteract against equipment failure like sensor failures.

The work is organized as follows: Chapter II gives an overview of the relevant state of the art, Chapter III shows and describes the workflow of the development of a basic control strategy for ventilating systems, Chapter IV gives an insight into fetching necessary data from Industry Foundation Classes (IFC) files and extending missing information with additional data as well as allocating geometry to given room zones, Chapter V shows how a working baseline control strategy is derived from this above-mentioned geometric data, in Chapter VI and VII some approaches to update and extend this baseline strategy are presented, Chapter VIII shows some results from the co-simulation process and Chapter IX gives an conclusion about this paper and an outlook for further work.

II. STATE OF THE ART

The digital, integrated BIM process is currently being established in Europe [4] and the US [5], having different levels of maturity in different countries: For example, BIM is standardized in the UK in the standard series BS1192 [6], whereas Austria has adopted the ÖNORM A-6241 [7] standard [8] to standardize properties that are used in BIM, e.g. material properties. In December 2018 the new ISO standard ISO 19650 [9] has been published, which provides international definitions of core BIM concepts like the Common Data Environment (CDE), the Exchange Information Requirement (EIR) and a Project Information Model. The Information Delivery Manual (IDM), which shall provide software interoperability during construction phase is standardized in ISO 29481 [10]. While standardization for planning and construction is well-developed, building services (planning and commissioning) and facility management are still in an early phase. Anyway, the basic definitions for building service components like sensors, actuators and controllers on which this paper relies are available.

To cooperate in a common planning and construction process, the BIM data needs a common data format to store the information. This data format is important for this work, since it provides access to the source of information. Different software manufacturers have defined proprietary data format: Revit [11], Allplan [12] or ArchiCAD [13] all have their own, incompatible data formats. Since this work intends to be independent of vendor specific formats, it has not been attempted to access these data formats. Instead, we focus on an open industry standard that allows the interchange of building data, namely the Industry Foundation Classes (IFC) [14] and the buildingSmart Data Dictionary (bsDD) [15]. IFC is a data format to describe, exchange and share building specific information. It covers physical and spatial components, resources, controls and actuators. Their naming is well defined in the IFC standard. bsDD builds on top of IFC and defines a library of objects together with their attributes. All common BIM software tools can export an existing model into IFC, which is the common denominator between different proprietary software tools. Therefore, we use IFC models in this work that have been exported as the BIM information source.

An IFC data file contains IFC entities with predefined structures. Some of this information is optional and can be skipped (using a dollar sign as a placeholder). This required data is either entered by using inverted commas or referring to another IFC entity, which has different labels, followed by a definite naming, e.g. IFCSpace. All IFC functions receive their own, unique number indicated with a hashtag, e.g. #11265, which provides a unique identification within an IFC model. An instance of IFCSpace can, for example be defined as:

ifcSpace(IfcGloballyUniqueId, IfcOwnerHistory, IfcLabel, IfcText, IfcLabel, IfcObjectPlacement, IfcProductRepresentation, IfcLabel, IfcElementCompositionEnum, IfcInternalOrExternalEnum, IfcLengthMeasure) [12]

All crosslinks need to have a specific IFC type. Thus, the very first task for reading data from the IFC standard is to identify all necessary IFC entities and their related IFC entities for reading out necessary indoor room and HVAC data. Hence, it is possible to identify, which of the above-mentioned optional data is used and which elements can be ignored. By defining both necessary IFC functions and their included types, the first task is completed, defining an ifcSpace example as:

#11265 = IFCSPACE('1l0Tb5MkzETxhlKNe2L0xv',#7,'RG 28',$,$,#11267,#11298, 'TOP 359',.ELEMENT.,. INTERNAL.,0.);

which represents the following data

globalId	1l0Tb5MkzETxhlKNe2L0xv
OwnerHistory	#7
Name	”RG 28
Description	$
ObjectType	$
ObjectPlacement	#11267
Representation	#11298
LongName	TOP 359
CompositionType	ELEMENT
InteriorOrExteriorSpace	INTERNAL

ElevationWithFlooring 0

The entity also contains cross-links: For example, the property ObjectPlacement, links to #11267, where the object coordinate system is defined; this system defines, whether the axis are absolute (relative to the world coordinate system) or relative (relative to the object placement of another product).

Today, most of the information in an IFC model is related to architecture and building geometry. As stated earlier, building services like a ventilation system also require the definition of components like fans, controllers, sensors and actuators. These components are partly already available in IFC version 4, with significant extensions currently being standardized.

IFC has been defined for about 18 years, and standardized for about 13 years [16]. However, neither IFC nor bsDD define a complete set of HVAC component and therefore also no automation components like HVAC controllers. A method to extend IFC files with control functions descriptions was defined by Benndorf *et al.* [17], which could be a simplification for obtaining necessary HVAC data.

Automatic generation of ventilation controllers from IFC data has great significance also. Different IFC parsers exist, such as IFCOpenShell [18], BIMserver [19], FZKViewer [20], although, partially they are only for 3D-representation of IFC data or do not provide an API that allows to link other programs for developing HVAC control strategies. Even if these parsers could provide necessary BIM data, no method has been developed to create control strategies for ventilation systems yet. Basically, three types of classical control methods for regulating the CO_2 level in buildings exist:

1. Constant volume flow controllers are the simplest ones, which are available in office buildings. Either controlled manually or within a fixed time, for example 7am to 8pm, a constant volume of fresh air is distributed into the supplied rooms.
2. On-Off controllers are mostly equipped with CO_2 sensors and hysteresis. If the given CO_2 set-point is exceeded, the volume flow controller is activated and will be deactivated as soon as a threshold is undercut.
3. PID controllers are demand controlled and need the current CO_2 concentration of a room also. In contrast to On-Off controllers, they allow a continuous control of the CO_2 level instead of a binary one. However, their parameters need to be defined. Equation (1) shows the control equation of PID controllers:

$$u(t) = K_P \left(e\left(t\right) + \frac{1}{T_I} \int_{0}^{t0} e\left(\tau\right) d\tau + T_D \frac{d}{dt} e(t) \right) \tag{1}$$

with the error e, the proportional gain K_P, the integral time T_I and the derivative time T_D.

Based on the given information about sensors and actuators from the IFC file, one of these basic controllers are used for controlling the CO_2 concentration of the rooms in the given building. For improving the behavior of standard CO_2 controllers, different methods have been published: Federspiel [21] described an on-demand control strategy, which requires the number of occupants for controlling the CO_2 level of a single room. This method would have to be adapted per room by hand, which is very time-consuming in larger buildings and does not include the interaction between all controlled rooms. So, even if the number of occupants is known, the strategy may fail, i.e. because of undersizing of the ventilation system. Shi *et al.* [22] described a method, which is based on direct feedback linear (DFL) theory and put forward in demand controlled ventilation (DCV). Again, this method was used for a single room and is not automatically created. So, for every single room, a new controller is necessary, which raises the developing effort significantly. Dasi *et al.* [23] described a method to update PID parameters by using fuzzy logic, however, they had to identify necessary parameters using the trial-and-error method, which again would need to be done for every single room separately.

Other methods, as described by Wang *et al.* [24] or Gu *et al.* [25], are using real-time data for adapting the controller's behavior. They are not appropriate to be used within the present task, since the developed algorithm is mainly used offline but in reality, the control strategy will be adapted quite often by changing BIM models.

Thus, none of these methods is appropriate for including them into an automation algorithm for ventilation systems, since the main advantage of the method presented in this paper is the automated update process for control strategies, whenever the BIM model changes.

III. WORKFLOW FOR CONTROL STRATEGY CREATION

As mentioned before, BIM is one of the most promising developments in the architecture, engineering and construction industry. For the current work, the biggest benefits are the accurate model of a building, which allows control strategies for indoor air quality to be developed quite early during the planning phase and to show potential needs for improvement. The flowchart in Fig. 1 shows the workflow for automated controller design that uses IFC data as a base for the creation of control strategies.

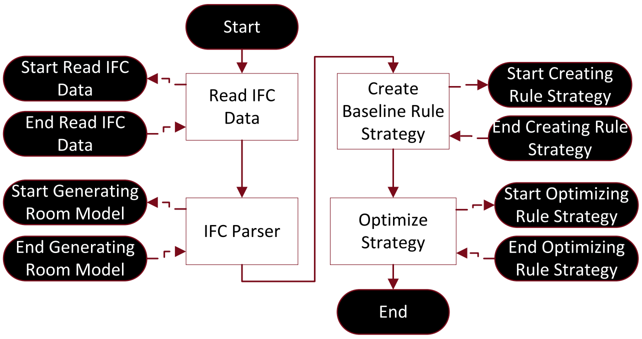

FIGURE 1. Workflow.

TABLE 1. Required data for automatically developing an air conditioning controller.

Type	Assess-able	Default assumption	Which data is needed?	
Room data	*No*	-	*Assigned room*	*Room type (office, lecture room, …)*
Actuators	*No*	-	*Assigned room*	*Actuator type (MFC, VFC, …)*
Max. volume flow inlet air	*Yes*	*ÖNORM EN 16798-3*	*Assigned actuator*	*Max. volume*
Sensors	*No*	-	*Assigned room*	*Sensor type (CO_2, presence, …)*
Window data	*No*	-	*Assigned room*	*Dimensions / area*
Door data	*Yes*	*Basic door with 0,80 x 2,1m*	*Assigned room*	*Dimensions / area*
Occupancy profile	*Partially*	*Derived from room function*	*Assigned room*	*Max. number of people allowed*

In the first step the IFC data is parsed to extract relevant information for the ventilation control: room dimensions, volume flows, available actuators and sensors, window and door sizes, the controller type and the occupancy profiles for each space in the building that shall be ventilated. IFC allows to store this information as *IfcPropertyValues*. Table 1 lists the necessary data; ''assessable'' refers to the possibility that a parameter can be estimated in case it is not given in the model.

Available data is extracted from the BIM model and augmented with additional data, if the model does not provide the necessary information. Since we seek a control strategy for a ventilation system, the system requires a CO_2 model that regards ventilation, natural dissipation and occupancy. Missing data like the occupancy profile can be derived from the definition of the room function: an office, for examples, provides 8m^2 for the first person plus additional 5m^2 per additional person, while a class room provides about 2,5m^2 per student. This allows to estimate the maximum number of persons; using the estimate for CO_2 production per person, which is defined in ÖNORM EN 16798-3:2017 [26], gives a baseline for air exchange rates. Other information that is commonly not available in a BIM are the overall opening hours of a building. This information must be provided so that the system can consider closing times with a different operation mode like nightly setback.

HVAC data and indoor data is used for developing a baseline control strategy. Within this process, every room gets its own specific ventilation controller that provides appropriate air flow and makes use of the available sensors and actuators (given that they are feasible for ventilation control). This baseline control strategy is based on the CO_2 model created from geometric data and does neither involve possible influences between different rooms nor occupancy variations.

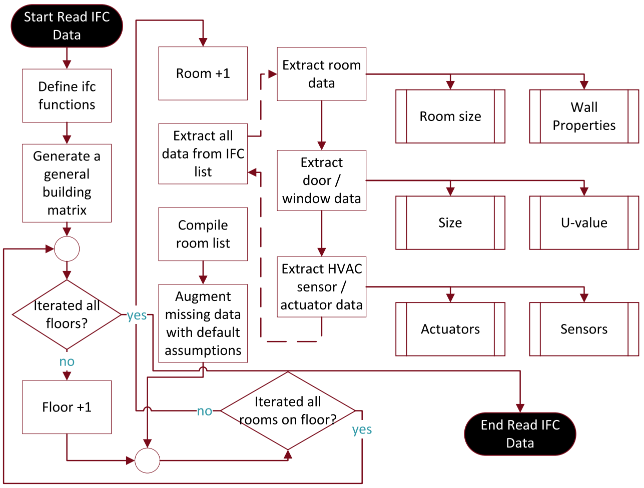

FIGURE 2. IFC data preparation flowchart.

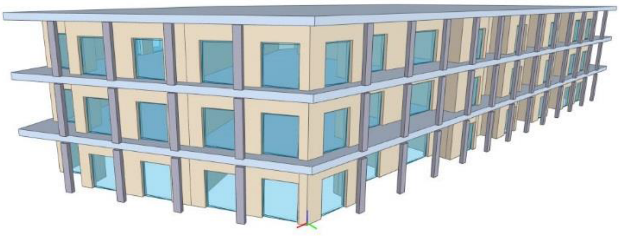

FIGURE 3. Building model for testing the allocating algorithm.

For optimizing the results, the controller will be updated during the runtime of the systems. Hence, variations of different occupancy profiles and appropriate controllers will be tested within a co-simulation environment and the results are saved in a data base for real time usage in the step.

IV. VENTILATION-SPECIFIC BUILDING MODEL

Depending on the buildings structure and on needed IFC data, different constant IFC entities are defined (*Define ifc functions*). With this information, the IFC parser can identify which entities are necessary for fetching data. The *readIFC* algorithm is shown in Fig. 2:

To create a control strategy, the room layout needs to be known. This information is stored in a room list, which contains all relevant ventilation information i. e. room sizes, wall properties, windows sizes and u-values, and relevant actuators and sensors for the ventilation system. Since BIM models are created in different authoring tools, the creation of the room geometry requires a separate algorithm (see Fig. 5), since relevant air (and heat) flows cannot be calculated if the function *ifcRelSpaceBoundary* does not exist. Typically, an air conditioning controller only improves the air quality of specific rooms, including offices, meeting rooms and lecture rooms. Hence, only these rooms need to be identified and their data fetched. Other rooms, such as corridors, lobbies, etc., get area-based volume flows, which do not require specific parameters. This simplifies the parsing process, since common office and lecture rooms mostly have quite simple room shapes (note that complex room shapes are not pursued

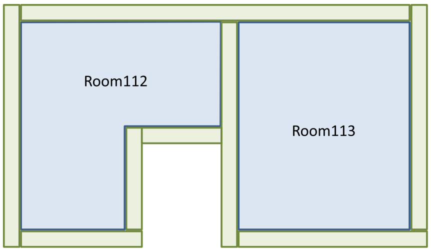

FIGURE 4. IFC wall allocation example.

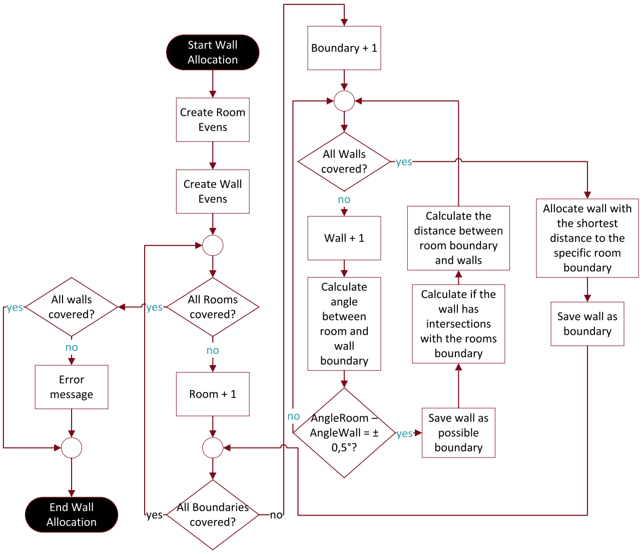

FIGURE 5. IFC wall allocation flowchart.

further in this paper). The resulting algorithm to allocate all walls to a specific room is discussed based on the building given in Fig. 3.

There, two rooms are taken, to show the algorithm's operating principle, see Fig. 4.

Two different spaces (blue) have their individual walls (green) and a single shared one. For understanding the following algorithm, it is necessary to know how such a space will be defined. Within IFC, room definitions start with the IFC entity *ifcCompositeCurveSegment*. This entity defines an *ifcPolyLine*, which creates a line between two points with *ifcCartesianPoint*. For example, Room112 is defined with six and Room113 with four poly lines. The same applies to the walls, which are defined with four poly lines. The flow chart in Fig. 5 shows the algorithm.

First, the rooms and the walls poly lines are used to create two dimensional lines:

$$g_i{:}X_i = P_i + v\overrightarrow{V_i} \tag{2}$$

for $\{i \in \mathbb{N} | i = [1; i_{max}]\}$ with the total number of room boundaries and walls i_{max}. g_i represents the specific line name, X_i any lines' point, P_i is a known point and $\overrightarrow{V_i}$ is the direction vector. All following calculations are based on vector algebra.

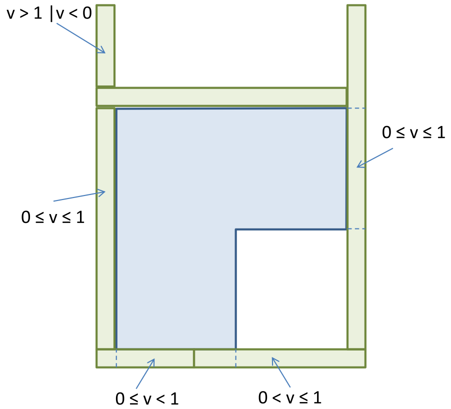

FIGURE 6. IFC wall allocation with shifted locations.

Equation (3) describes the calculation of the enclosed angle between the m^{th} wall w and the n^{th} room r, which is needed for identifying whether a wall is a possible boundary of a room:

$$\cos\varphi = \frac{\overrightarrow{V_{wm}}\,\overrightarrow{V_{rn}}}{\left|\overrightarrow{V_{wm}}\right|\left|\overrightarrow{V_{rn}}\right|}. \tag{3}$$

Deviations could occur through a high number of decimals, whereby a hysteresis of ±0,5° is an acceptable angle deviation between the room's boundary and the wall. After identifying all possible boundary appertaining walls, the condition

$$\begin{aligned} P_{wm} + v\overrightarrow{V_{wm}} &= g_{rn}(u{=}\,0){+}w\overrightarrow{n_{Vrn}} \qquad (4)\\ P_{wm} + v\overrightarrow{V_{wm}} &= g_{rn}(u{=}\,1){+}w\overrightarrow{n_{Vrn}} \\ 0 \le v &\le 1 \qquad (5)\end{aligned}$$

needs to be checked. Thereby, all wall points between its beginning, $v = 0$, to its end, $v = 1$, need to be part of the rooms boundary. This additional check is necessary because of the infinity of a line. Otherwise, parallel lines without any contact point could be identified as boundary appertaining walls, see Fig. 6.

The wall with the shortest distance d to the room's boundary is the appropriate one, which will be calculated by

$$d = \frac{|(P_{cwm} - P_{crn})| \times \overrightarrow{V_{rn}}}{\overrightarrow{V_{rn}}} \tag{6}$$

whereby P_{cwm} is the center from the wall and P_{crn} those from the rooms' boundary.

After identifying all walls for every room, the room list can be filled. For a well-mixed space, the mass balance of CO_2 concentration can be calculated by

$$V\frac{dCO_2}{dt} = \dot{C}_{CO2} + \left(CO_{2,out} - CO_{2,in}\right) nV \tag{7}$$

with

V	Air volume of the room in m^3
$\frac{dCO_2}{dt}$	CO_2 level change within the next time step in ppm/s
$\dot{C}_{CO2}$	CO_2 production inside the room in ml/s
$CO_{2.out}$	CO2 level from outside in ppm
$CO_{2.in}$	CO2 level from inside in ppm
n	air change rate caused by windows, doors and the ventilating system in 1/s

This approach can be frequently found in different references, as in [27]. Based on this non-linear equation and the maximum number of people allowed inside the room a linear PT1 element is estimated. This is an eligible simplification, since the CO2 level, where this equation is used, is within a limited range: the indoor CO_2 level will normally change within 400ppm and 2000ppm. After approximating the PT1-element, the parameters K_P (proportional gain) K_I (integral time) and K_D (derivative time) were identified using the general guidelines for the Ziegler-Nichols tuning method, [28].

Depending on IFC data, the ventilation systems type is defined, too. Basically, two different systems exist:

- Centralized and
- Decentralized.

The main difference is the number and size of installed ventilators. While a centralized system has a single ventilator for fresh air and one for exhaust air, the decentralized system has one ventilator per room or zone. That leads to higher installation efforts and costs, though Variable Air Volume (VAV) controllers are not needed, and the amount of fresh air is easier controllable. VAV controllers are needed in decentralized systems, because the ventilation system only provides a maximum amount of fresh air and does not control the volume flow by room. So, VAV controllers are needed, which change the flap position to affect the volume flow into a room. Based on this information, different control strategies are defined in Chapter V.

V. GENERATING A BASELINE CONTROL STRATEGY

After the BIM model has been parsed to extract relevant geometry and component data, it is possible to create a baseline control strategy that ensures comfort in each room and makes use of the available sensors and actuators. The creation process relies on a library of control blocks that are used to compile a control strategy, which has been defined in this work by means of Simulink blocks. The most relevant blocks of this library are shown in Fig. 7.

The "PAR_" inputs are used for configuration of parameters, the other inputs are connected to sensors or other given values, whereas the outputs are connected e. g. to actuators. *Air Quality Controller* represents a controller with a fixed volume flow, this is the simplest controller and can be used for a baseline control strategy. *AirQualCtrlPres* is a linear PID air quality controller that uses a CO_2 sensor (Q_ROOM) and has an additional presence sensor (P_AUTO) whereas *AirQualCtrlNoPres* is an air quality controller without presence sensor. *MFC* is a mechanical flow controller that provides a constant volume flow. *Presence Detector* was introduced for clarity, to show that such a sensor exists in the real system. *Follow Up Time* is a block that delays its output signal for a given period after the input has been disabled and can be used for a fixed period of ventilation after the last presence detector was triggered. *SchedulerDoW* is a time scheduler block which can be configured individually for each day of the week. This component is commonly used in building SCADA systems for setting global operation schedules.

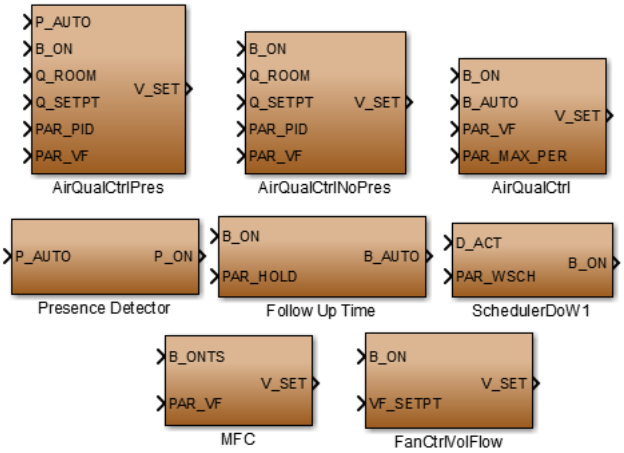

FIGURE 7. Simulink library of control blocks for air conditioning.

TABLE 2. Default parameter values for an office building.

Block	Parameter	Value
Follow Up Time	PAR_HOLD	600 [s]
SchedulerDoW	PAR_WSCH	07:00 – 20:00 [hh:mm]
AirQualCtrlPres, AurQualCtrlNoPres	Q_SETPT	1000 [ppm]

Before these controllers can be used, they must be configured using the "PAR_" inputs. Depending on the different room sizes and workloads, these parameters need to be updated. Thus, these blocks will be used within the optimization of the baseline control strategy. The configuration of controllers like the *AirQualCtrlPres* require to set "PAR_VF", which is the maximum volume flow that this volume flow controller can provide. This information typically is one of the IFC properties that describe the *ifcController* object. Note that such parameters need to be standardized before becoming broadly accepted; this standardization process is currently not finished.

As explained earlier, data which cannot be extracted from the BIM model has to be filled by default assumptions. Similarly, most of the parameters for the control library blocks have default values. For example, in case of an office building, the values are set, as seen in Table 2.

Within the first steps of the control strategy generation, a general HVAC template is defined, which contains the basic structure of the air ventilation system. That simplifies the

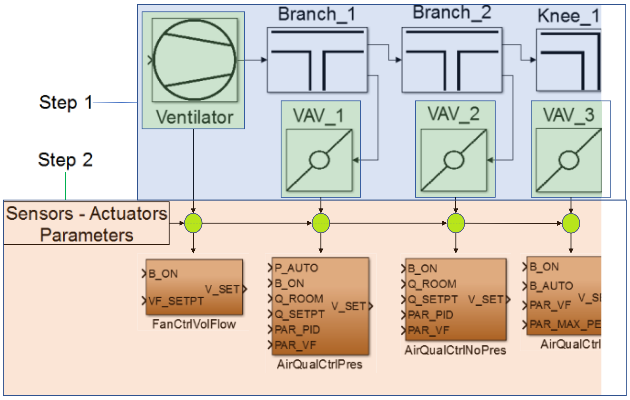

FIGURE 8. First steps of generating a baseline control strategy.

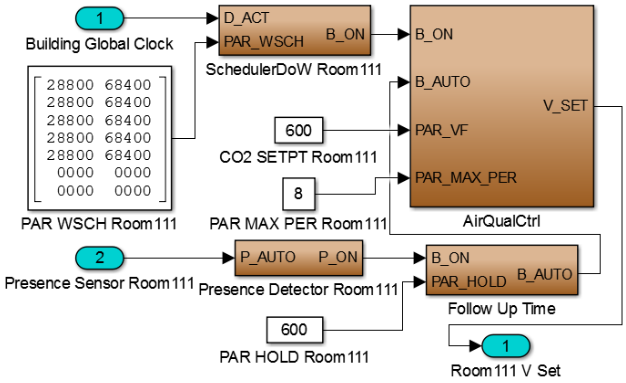

FIGURE 9. Automatically generated SIMULINK air conditioning controller for a single room.

control strategy definition significantly and serves as a basis for identifying necessary control blocks. As a second step, all available sensors and actuators, as well as parameters, are identified per controller. That leads to related HVAC blocks and necessary sensor-inputs, actuator-outputs and constant blocks for parameter definition, see Fig. 8. Finally, this new control strategy is compared with existing, which are stored in the data base. There, the rooms and windows sizes as well as the maximum allowed number of persons and available actuators and sensors are matched, and possible updated parameters are adopted.

After identifying all subcomponents of the air ventilation system, they are processed separately and connected in a general control environment. As an example, VAV_3 is discussed in more detail.

Depending on unassociated inputs of the controller block, related extension blocks are inserted and connected. For example, B_ON expects a binary signal from any block, which (de)activates it. In the present case a time-scheduler is added, since the building type is a university and this specific room a lecture room. That leads to the assumption, that during weekends and nights, no CO_2 emission is emitted, and the room does not need to be ventilated at all. Another extension block implements a so-called follow-up time. This block is combined with available presence detectors for (de)activating air conditioning for a more energy efficient operation.

When every blocks' input is connected, either with an extension or with a constant block for parametrization, the parametrization process starts. Thereby, every room's air quality controller is either parameterized for the maximum number of people, which are present in this specific room, or depending on given information, which was fetched from an IFC or csv file. Therefore, the parameters of the CO_2 room model are set using the information about room size, the number and size of windows and doors, and an occupancy profile with the above-mentioned number of people. Afterwards, the fixed volume flow from $15m^3/h$ per person will be determined, [26].

Fig. 9 shows such an automatically generated SIMULINK model for air conditioning a single room.

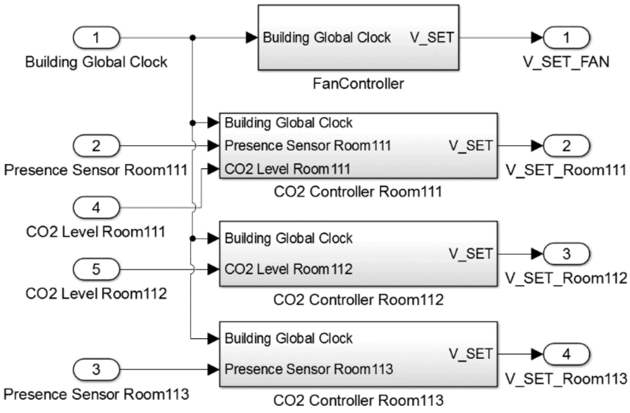

FIGURE 10. Final baseline controller.

Blocks with brown background color originate from the control block library, cyan blocks are sensors and actuators and white blocks are adaptable parameters. The complete ventilation system controller for this simplified example is shown in Fig. 10.

VI. UPDATING THE BASELINE CONTROL STRATEGY

The previously described process provides a building with a control strategy from the first day of operation and without the need for human interaction. During operation – once the building has been constructed – it may be feasible to re-evaluate the control strategy and react on different usage scenario or equipment failure.

The system presented here has potential to further optimize operation using measurement data. It is assumed that the optimization is executed regularly e.g. once a day and evaluates the recent historic data.

A first check is for equipment failures: Plausibility checks on the presence detectors reveal if a sensor is malfunctioning, e.g. by providing no occupancy information in a room or claims constant presence (although the CO_2 measurements indicate otherwise). In this case the system can replace the controller block for the respective room with a controller that does not use presence detection (*AirQualNoPres*).

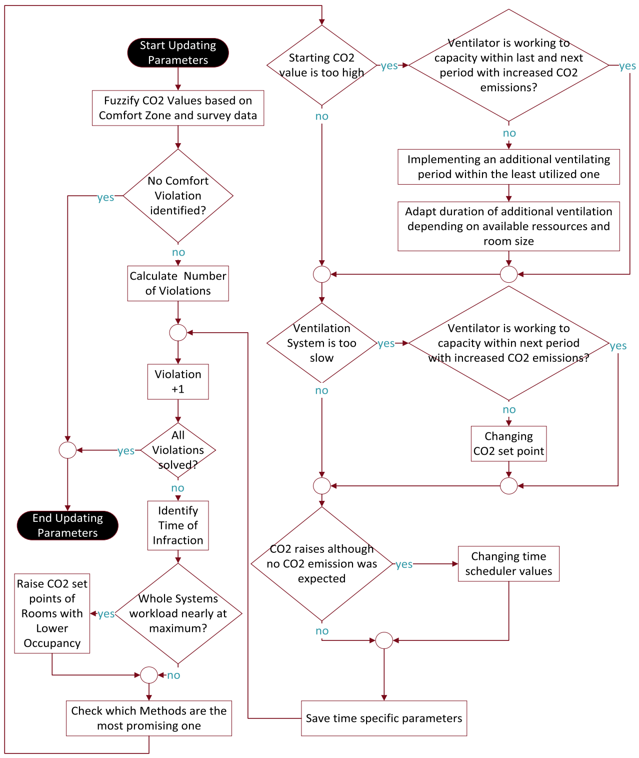

FIGURE 11. Updated rule strategy generating flowchart.

TABLE 3. Fuzzification table.

Rating	CO_2 Level [ppm]	DP [%]
Great	*<1000*	*<18*
Acceptable	*1000 – 1500*	*18 – 28*
Still Acceptable	*1500 – 2000*	*28 – 36*
Unacceptable	*>2000*	*>36*

Plausibility checks on the CO_2 sensor values can indicate that a CO_2 sensor is faulty (e.g. due to lack of calibration or interrupted communication). In this case the system can replace a controller block with a constant air volume controller that disregards the CO_2 level in the room. While not as energy efficient, it is still a resilient solution that keeps the system operational.

The next ability requires the analysis of CO_2 levels in all rooms supplied by the same ventilation system. In Fig. 11, the workflow of a parameter updating algorithm is shown.

First, the comfort level and the energy consumption are weighted. Thereby, the correlation between dissatisfied persons (DP) and the difference between the inside and outside CO_2 level ($CO_{2,\text{diff}}$) is calculated by [29]:

$$DP\left(CO_{2,diff}\right) = 395e^{-15.15CO_{2,diff}^{-0.25}}. \tag{8}$$

Using the CO_2 limits from [30] and [31], Table 3 and Fig. 12 were created for weighting the usefulness of improving the CO_2 level in a specific room:

These fuzzification values can be manipulated during real time operation, e.g. fed with survey data, whereby the whole updating process restarts. Basically, the results of the fuzzification process are used for defining acceptable limits for the CO_2 set-points; in the present example these limits are set to 1000-1500ppm. Thus, the algorithm focuses on improving the indoor comfort level and sets different CO_2 set-points for reaching an energy-efficient and convenient operation. Furthermore, during the improving process, values within these fuzzified limits are compared between all rooms and it is checked whether a comfort level reduction in one specific room is in an appropriate relation to the comfort level improvement in another one.

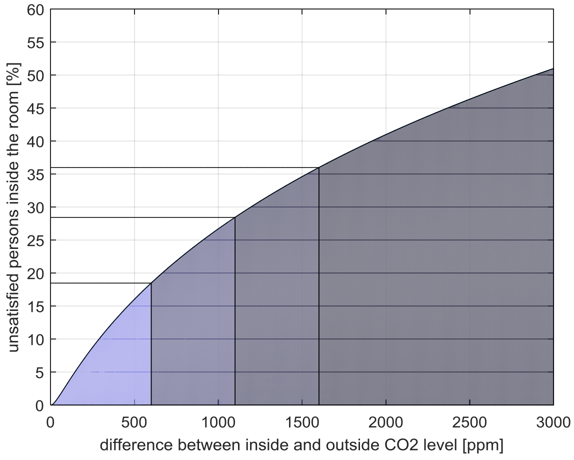

FIGURE 12. Area of unsatisfied persons depending on the CO_2 Span which is set for fuzzifying.

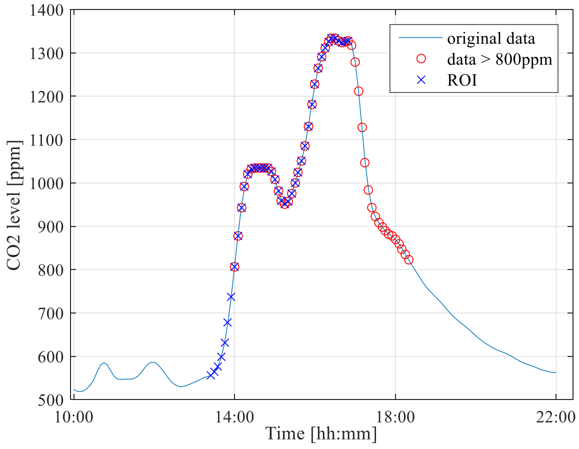

FIGURE 13. Result of identifying ranges, where people are inside the specific room.

After fuzzifying the CO_2 values, the range of interest (ROI) needs to be defined to identify violations of the comfort zone. This range subjects to certain conditions:

- CO2 value is higher than 800ppm and
- persons are inside the room.

First, measured data needs to be smoothed because of partially erroneous measurements. Therefore, locally weighted linear regression with a span of 12 measured points is used, where outliers are deleted, though the original shape of the curve has not changed significantly, see Fig. 13. Present data is taken from a CO_2 sensor, which is installed in an existing ventilation system. For better readability, only a single day is shown.

Fig. 13 shows all sensor data during a time of occupancy with a CO_2 concentration above the user-specified threshold of 800ppm. As a test sample, data is taken from an earlier project called ARIS, [32], where CO_2 levels were measured during lecture time in an university.

After these pre-calculations, the algorithm follows the flowchart shown in Fig. 11. First, the total volume flow from this ventilation system is compared to the maximal possible volume flow. If the ventilators' workload is nearly at maximum, the comforts improvement is very limited. Hence, resources are released by globally optimizing the air volume flow: by raising the CO_2 set points from less occupied rooms, the algorithm trades lower comfort in little occupied rooms (but still in accordance with Table 3) with a reduced comfort violation in highly occupied rooms.

VII. FURTHER OPTIMIZATIONS BASED ON EXTENDED DATA

Another possibility for optimization is to examine the controller dynamics compared to the occupancy and room dynamics. If an overshoot in the CO_2 level of a room is detected, which is only temporary before a high-load situation, it may be due to reasons:

- The starting CO_2 level is too high
- The controller reacts too slowly

For solving these issues some programming solutions are presented. If the starting value is too high, the systems workload is checked before this specific and the last range of interest (ROI). Given that the controller has access to predefined room schedules, assuming the expected occupancy in near future is possible. Thus, either a pre-air conditioning or a follow up time is implemented (i. e. the ventilation system maintains operation even if there is no more occupancy until the minimum CO_2 level is reached). If the controller response time is too low, the systems workload is checked before and during this specific ROI. Either a pre-air conditioning or a lower CO_2 set point is implemented. All solutions lead to a better CO_2 level within the ROI, as shown in Chapter VIII.

After solving occurring comfort violations, a method for improving the comfort level was developed. For that, the fan characteristic is read out from the available IFC file. The manufacturer typically provides some operation point measurements, as shown in Table 4.

This data is taken from [32] again and is approximated with a third order polynomial function, as shown in Fig. 14. Cubic order was chosen because of the idealized power consumption (9), [33].

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \tag{9}$$

TABLE 4. Measured volume flow over power consumption data.

Volume flow [m³/h]	Power consumption [kW]	Volume flow [m³/h]	Power consumption [kW]
0	*0*	*4500*	*1,08*
500	*0,25*	*5000*	*1,375*
1000	*0,27*	*5500*	*1,83*
1500	*0,28*	*6000*	*2,29*
2000	*0,29*	*6350*	*2,7*
2500	*0,31*	*6500*	*2,94*
3000	*0,375*	*7000*	*3,58*
3500	*0,5*	*7500*	*4,25*
4000	*0,75*	*7650*	*4,6*

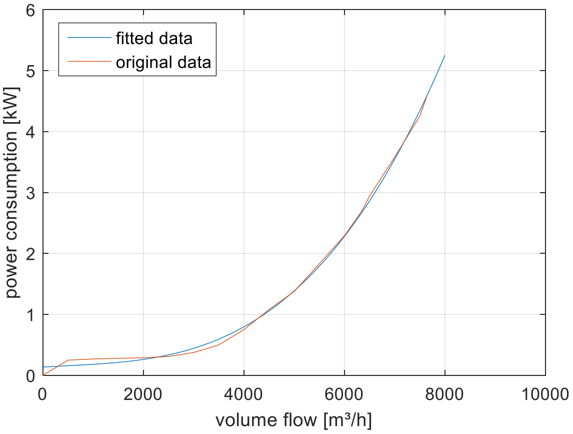

FIGURE 14. Comparison between real ventilator characteristics and approximated 3rd order polynomial function.

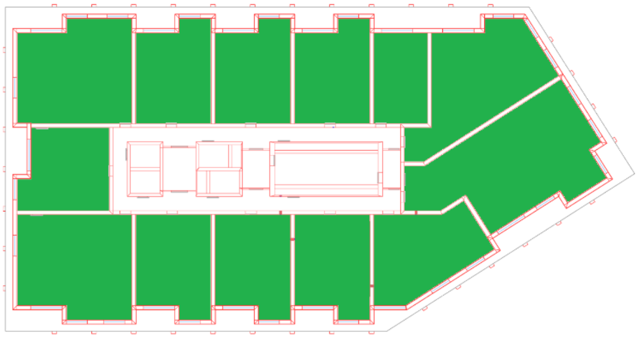

FIGURE 15. Automatically identified rooms.

with the power consumption P_1, P_2 at the rotational speed n_1, n_2 and the relation

$$\frac{\dot{V}_1}{\dot{V}_2} = \frac{n_1}{n_2} \tag{10}$$

with the volume flows $\dot{\mathrm{V}}_1$ and $\dot{\mathrm{V}}_2$.

All these controller updates are stored in a data base depending on different occupancy. If any unforeseeable events occur, the controller chooses the best fitting control strategy from the data base. This leads to greater freedom and better results during real time usage.

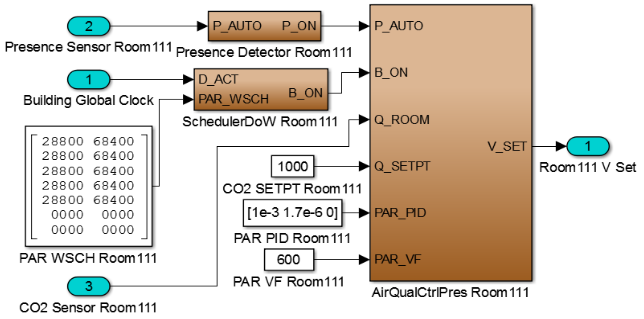

FIGURE 16. **Automatically developed air conditioning controller for a single room.**

VIII. RESULTS AND DISCUSSION

We validate the proposed methodology using a BIM model from a real-world planning process, which is available in IFC4. As expected, the model did not contain the required building service components, especially VAV controllers, ducts and fans were missing – this information had to be added as a separate data source. The IFC parser identifies all available rooms and filtered non-ventilated spaces (e. g. halls). Fig. 15 shows all 13 rooms, whichwere identified.

The rooms' walls were not allocated to the room's boundaries, therefore the algorithm for wall allocation as described in Chapter IV, was applied. Their properties were filtered from the basic IFC file and stored in the database. For example, room 'TOP 336' has the following properties:

Area	52,08 [m^2]
Height	2,77 [m]
Window	1 3,52 [m^2]
Window	2 5,28 [m^2]
Door	1 1,80 [m^2]
VFC	yes
Presence Detector	yes
Max. number of people	20

and the room definition "seminar room". With this information a controller was automatically developed (see Fig. 16), which includes all available sensors and actuators. For first estimations of the results from a real system, a simulation environment was built up. For that, the co-simulation program PTOLEMY [34] was used. There, the controller was developed as a SIMULINK [35] model and the simulated real world was modeled in TRNSYS [36]. The simulation with two different programs is performed in order to clearly separate the automatically created controller and the virtual real world.

For the sake of clarity, the following figures show the results of only a single day and 7 of 13 rooms.

Fig. 17 shows the simulation results of the automatically generated basic controllers. During this day the ventilators workload is not reached, wherefore all controllable (lecture) rooms reached their desired CO$_2$ value. Office rooms have built in a mechanical volume flow controller, which can only be turned on or off depending on the overall ventilation systems status. Fig. 18 shows the simulation results of the automatically generated basic controllers. During this day the ventilators workload is not reached, wherefore all controllable (lecture) rooms reached their desired CO$_2$ value. Office rooms have built in a mechanical volume flow controller, that can only be turned on or off depending on the overall ventilation systems status.

Even though the controller works fine during standard situations, on the one hand problems could occur, on the other hand the comfort level and the power consumption could be optimized too. First, a quite common occurring problem is discussed: the ventilation systems workload is at nearly maximum and some of the rooms do not get as much fresh air as needed for reaching their desired CO$_2$ level, as can be seen in blue in Fig. 18.

Therefore, pre-air conditioning was implemented, and the starting CO$_2$ level was reduced from about 700ppm to 600ppm. Thus, within the first 30 minutes a much better comfort level was ensured. At about 12:50, the systems workload dropped, and the considered room was able to reach the desired CO$_2$level in both cases again.

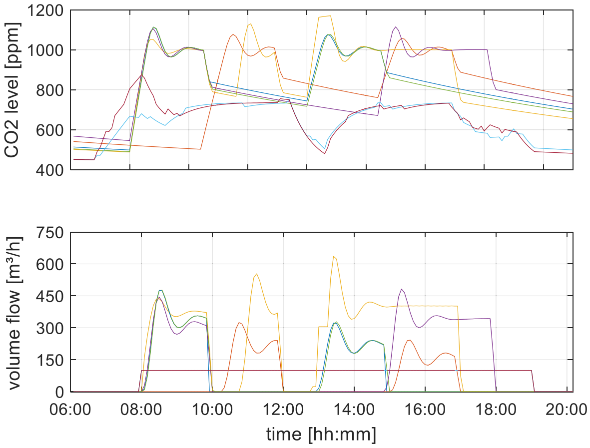

FIGURE 17. **Simulation results, using an automatically generated basic CO$_2$ controller.**

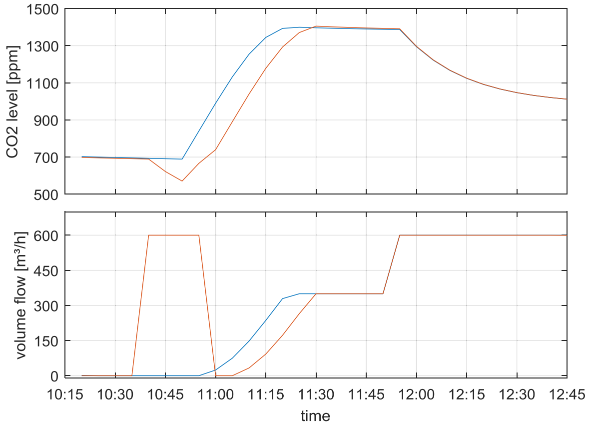

FIGURE 18. **Improving comfort by using pre-air conditioning.**

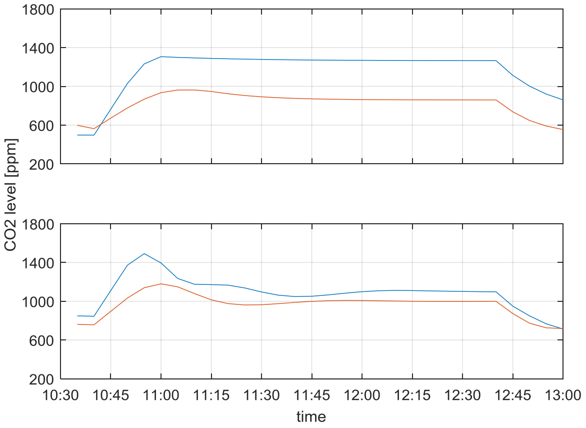

FIGURE 19. **Improving comfort by changing other room's CO_2 set-points.**

Another approach includes the total air volume from all rooms and their specific CO_2 levels. For providing more fresh air in undersupplied rooms, well supplied rooms' set points could be raised. Thus, their CO_2 level worsens, even though another rooms' CO_2 level may drop into an acceptable range, as seen in Fig. 19.

These two methods were developed for avoiding bad comfort levels in undersupplied rooms caused by an undersized ventilation system.

The approach, which was presented in Chapter VII, was used to improve the comfort or decrease the energy consumption by comparing the CO_2 level improvement / deterioration and the resulting higher / lower power consumption.

IX. CONCLUSION AND OUTLOOK

The development of international standards for BIM modeling is currently at an advanced stage. Thus, advantages of such a standardization can be used for developing air quality controllers. Within this continuous development, potential for improvement can be identified. This paper shows a way of identifying and completing missing information, which is necessary for developing air quality controller, from IFC data-sets and extending these partially incomplete sets. Different basic prerequisites need to be satisfied within a geometrical model. Due to the lack of standardization, missing data for HVAC components had to be added from additional data sources.

Based on this prepared information, HVAC control strategies are developed, which can be implemented in real systems. The greatest advantage is the direct impact of changes in the geometrical model on the controller's development and behavior, which is independent on human action. However, the main disadvantage is apparent: The controller development is dependent on the data quality of the given IFC file and additional information. Mistakes during model generation or incorrect data may cause the controller not to work appropriately. Even if these errors occur, fault detection and fixing them is easier and much less expensive than within construction phase. Additionally, the basic building's behavior on changing occupancies and different controller data is verifiable. Varying room sizes with different occupancies can be compared, as well as different controller types and their impact on total energy consumption, as well as on the comfort level.

Based on the creation of basic control strategies, we have shown additional approaches to improve the air quality and the controllers' performance using occupancy profiles in different rooms. Different alternative controllers are stored in a database and can be used for comparing different controller combinations within the ventilating system.

These approaches require very precise data-sets, since every mistake influences the control strategy development directly. This requires international standards and highly experienced BIM developers for avoiding additional efforts. Additionally, BIM acceptance needs to be increased in commerce, where automatically generated controller may contribute as another advantage in addition to more obvious advantages as less mistakes during construction process.

Within this paper the focus was on fetching data from IFC, checking and extending them with necessary additional data and automatically generating a control strategy for ventilating systems, basically. Though, a more complex part of HVAC controllers is the development of controllers for providing and distributing heat in a building. Especially, the rapid growth of renewable energy systems and their energy-efficient operating without violating the comfort zone leads to problems, which could be solved by using automatically generated control strategies within the planning process with BIM.

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ANDREAS SPORR studied microsystem engineering and mechatronic systems from the University of Wiener Neustadt and received the M.Sc. degree, in 2016. He is currently pursuing the Ph.D. degree with the Austria Institute of Technology, Seibersdorf, Austria, and TU Wien, Vienna, Austria.

During his master's thesis, he was with the Austrian Institute of Technology. After his knowledge acquisition in image manipulation during his bachelor's thesis, he deepens his knowledge in co-simulation, control technology, and model design during his master's and his continuing Ph.D. thesis. Within these theses, he was involved in the project ARIS and is a project member of KORE.

GERHARD ZUCKER finished his viva-voce exam with excellence at TU Wien, in 2006. He is currently with the Austrian Institute of Technology (AIT) in sustainable building technology. He is also a Senior Scientist, working in application oriented research focusing on building automation and artificial intelligence and building information modeling (BIM). His publication record includes editorship of two books and 15 journal publications in the last 5 years. His research interests include smart building technologies for the optimization of energy efficiency in buildings.

Dr. Zucker is active as a Session Chair and a Track Chair in various conferences, the latest being track chair at the IEEE AFRICON 2017 and the IECON 2018. He is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS. He is active in standardization with the Austrian Standards Institute (ASI Komitee 11.09 BIM) and the CEN TC 247 WG4 Open System Data Transmission.

RENÉ HOFMANN has been a Professor and the Head of the Research Group Industrial Energy Systems, Institute for Energy Systems and Thermodynamics, TU Wien, since 2015. He is a Thematic Coordinator with the AIT Center for Energy, Sustainable Thermal Energy Systems.

He has many years of experience and publications in thermal and industrial engineering and was active as a Senior Process Engineer with R&D at Josef Bertsch GmbH & Co. KG, Austria. His current research interest includes design and operational optimization of energy systems for complex industrial and energy production systems.

Prof. Hofmann teaches methods for modelling, simulation, and optimization of thermal processes and components. He is a Scientific Coordinator of the Cooperative Doctoral School SIC! [Smart Industrial Concept] and active as alternate delegate in the executive committee of the technology collaboration programme Industrial Energy-Related Technologies and Systems (IETS) of the International Energy Agency (IEA).

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