SCALABLE BUILDING ENERGY EFFICIENCY BALANCING

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ABSTRACT

Buildings, especially existing buildings, consume too much energy in a way we do not monitor and control continuously. Such overconsumption both substantially counteracts efforts to slow down climate change and is financially costly, which is a highly pressing topic in current times. Yet under the premise of applying Building Information Modeling (BIM), the automated and scalable generation of digital twins from building models for building energy efficiency balancing is feasible as we demonstrate. Consequently, existing and new buildings can be twinned for building energy efficiency balancing both to identify necessary refurbishments for existing buildings, and, in the event of new buildings, take the right decisions during the planning and design, and operation phase, respectively. Our proposal has been evaluated in the course of expert interviews to verify both its practical feasibility and relevance.

Keywords: digital twins, energy efficiency balancing, Building Information Modeling (BIM), Building Energy Modeling (BEM)

1 INTRODUCTION

Buildings consume too much energy [1]. To enable energy efficiency balancing, scalable, retrofittable, and pervasive monitoring and control infrastructures that do not degrade the comfort of living are required. Modern buildings, in theory, already possess the capacity for energy efficiency balancing by comprising complex cyber-physical systems (CPS) with an embedded monitoring and control infrastructure. Consequently, with the application of Building Energy Modeling (BEM), i.e., the process of simulating and analyzing the energy performance of a building to optimize its energy efficiency and environmental impact as an integrated part of the planning and design phase, energy efficiency can be optimized early in the design and planning phase. This workflow, called BIM2BEM is strongly evolving, but not yet scalable in practice epitomizing consequent energy waste [1]. To succeed, BIM2BEM capitalizes on smart buildings – either from as early as the planning and design phase or through posterior refurbishments.

Smart buildings comprise intelligent networking and automation targeting increased comfort and reduced energy consumption [2]. The prerequisite for designing such a building is an integral optimization task of the architectural design and the specialist designer. The common denominator is an energy balance calculation by a dynamic simulation of the building under design by a digital twin starting from a BIM model, i.e., a high-fidelity, digital representation of the physical and functional characteristics of a building. Information about 3D geometry, building elements, and HVAC components is extracted from the BIM model if there

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is an adequate BIM2BEM-workflow established. The IFC standard [3] is suitable for classic rule-based information extraction and is currently the only data model that is sufficiently standardized. Modeling IoT devices as part of the IFC, however, is not yet common, but will be in the future [4]. This is where all elements conflate: under the use of BIM2BEM, smart buildings are energy efficient by design, and augmented by a digital twin for simulation. The digital twin is the intersection point for designing, commissioning, controlling, and computer-aided facility management (CAFM).

Digital twins (DT) [5] describe virtual information constructs replicating a physical asset and comprise [5], viz. a (i) *virtual instance*, i.e., the assemblage of system, test, product, and simulation models which replicate the physical asset, (ii) a *product instance*, i.e., the physical asset, and (iii) *interchanged data and connections*, i.e., bidirectional communication between the virtual and product instances, respectively. We conjecture that the successful application of BIM paves the way for the gestation of DTs for the architecture, engineering, construction, and operator (AECO) domain [6], i.e., for building energy efficiency balancing in the context of BIM2BEM, among others [6]. The tight resemblance between BIM and DTs radically epitomizes in linking BIM with the IoT [4].

In our paper we report on a *scalable* and *integrated* environment for building energy efficiency balancing thereby contributing (i) a fully automated and scalable DT platform for building energy efficiency balancing, (ii) automated bidirectional twinning of the virtual and physical instances, and (iii) a scalable, integrated solution for energy efficiency balancing early in the planning and design phase, and later on, in the operation phase. Our contribution is structured as Design Science Research (DSR) [7] and delivers an artifact to facilitate building energy-efficiency balancing. Development is initiated with the phase of requirements elicitation and concludes with cyber-physical prototyping, experimentation, and expert interviews. Our artifact is deployed as a treatment for the following design problem, expressed using the DSR template [7]:

Improve *BIM2BEM* (context)
by treating it *with a digital twin* (artifact)
to satisfy *a scalable and integrated workflow* (requirement)
to balance *a building's energy efficiency*. (goal)

Definitions and Terminology

To merit understanding of our contribution, we briefly outline key terms and their definitions:
Scalability is a system's capacity to adjust performance and cost to application and system processing needs, e.g., in the event of using larger and more complex models for creating a DT.
Energy-balancing aims at matching supply with demand, which is important to keep systems within safe operating limits. For electricity, this needs to be done on a second-by-second basis.
Twinning refers to establishing a data exchange link between a physical asset and its digital counterpart.
Bidirectional Twinning refers to establishing bidirectional data exchange between physical and virtual assest, as compared to uni-directional exchange which would only result in a digital shadow (cf. Figure 1).

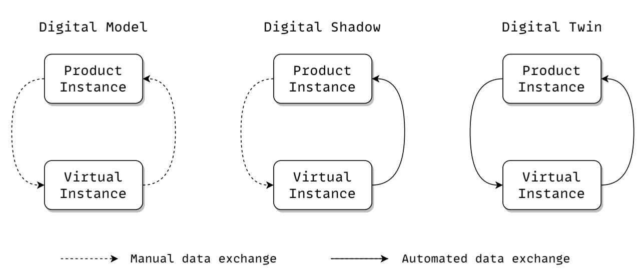


Figure 1: Types of DTs by their level of twinning [8].

The remainder of our contribution is structured as follows. Section 2 elicits requirements for our contribution. Section 3 introduces the components of our environment for building energy efficiency balancing. Section 4 evaluates our environment and positions our work concerning related work. We conclude in Section 5 with an outlook on future work.

2 REQUIREMENTS

From a DT perspective, the use case of energy efficiency balancing is both novel and unique by comprising (i) a heterogenous design and planning scenario where designers and specialist planners work with the DT, and (ii) an operating, or runtime scenario where the DT is employed for monitoring and control as part of energy efficiency balancing and CAFM (cf. Figure 2). The heterogeneity of the design scenario results from both building designers and specialist planners, e.g., energy planners, traditionally employing incompatible modeling formalisms in their work [9]. This drastically impedes scalability [R1] and reusability [R2] by imposing preparatory labor by manually federating models [9]. Consequently, a single unified model (SUM) [R4] using the IFC is beneficial. Observe that [R1] and [R2] readily deliver the capacity to not only twin single buildings but eventually complete cities [9]. In addition, the reliance in models (e.g., the SUM) enables a high degree of automation, a core requirement for the automated deployment of DTs [R11] readily rendering the DT the operating model for the building.

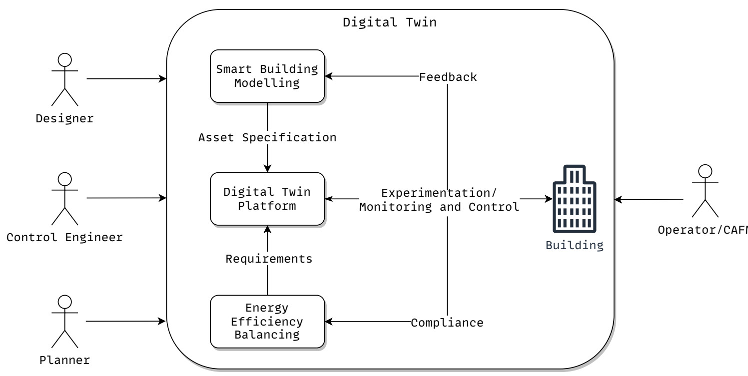


Figure 2: DT landscape.

The twinning of complete cities demands automated and efficient synthesis of a DT cockpit [R9] for visualizing both complex buildings and data. The amount and quality of available data, cf. [R5] and [R6], for energy efficiency balancing substantially depends on the capacity to automatically twin with a building [R8]. To autonomously control and balance a building's energy efficiency during its operation phase, bidirectional communication [R8] with the actual building enables the remote controlling of embedded actuators, e.g., a heater (cf. Section 3.1). This requires interoperability [R10] for twinning with different communication interfaces on part of sensors and actuators, but also for integrating 3rd party services (e.g., weather forecasts). Different buildings may require alternate strategies to reactive control as we investigate (cf. Section 3.1.2), thus motivating the need for predefined extension points to implement additional control strategies [R7].

Finally, in the context of BIM2BEM, which ultimately aims at reducing the total energy consumed by buildings, the DT and its environment should keep energy consumption as low as possible and not induce excess consumption [R3]. Further, to thereby not decrease the comfort of living in already existing and inhabited buildings, the pervasiveness of our treatment [R12], i.e., a non-visually and audibly perceivable monitoring and control infrastructure is paramount. Table 1 summarizes the requirements for our environment for building energy efficiency balancing.

Table 1: Requirements for our DT platform for energy efficiency balancing.

R1	Scalability	**R7**	Extensible Controller API
R2	Reusability	**R8**	Bidirectional Communication
R3	Low-energy consumption	**R9**	DT Cockpit Generation
R4	Single-unified Model	**R10**	Interoperability
R5	Real-time Data Integration	**R11**	Automated Deployment
R6	Historic Data Provisioning	**R12**	Pervasive

3 ARTIFACT ARCHITECTURE AND IMPLEMENTATION

Our contribution primarily was designed with a claim for pervasiveness and scalability and the target vision of building energy efficiency balancing. In the following, we discuss our contributions and how it merits these aforementioned design goals.

3.1 A Pervasive Infrastructure for Building Monitoring and Control

To monitor and control building energy efficiency, solutions that do not degrade the comfort of living are imperative. Recent advances in the IoT, specifically, in remote sensing and control in conjunction with BIM [4], provide a fertile ground for designing our monitoring and control infrastructure as outlined in Figure 3 and comprises multiple components: a cable-bound sensing system, a wall-embedded RFID sensing system, a data system that handles the processing and storage of data, a user interaction system, and a heating system. In addition, it comprises a time-series database, a web interface, and 3rd-party libraries for the cable-bound system. The heating system can be both remotely controlled or by reactive control (Section 3.3.2). The WebApp delivers the DT cockpit (Section 3.3).

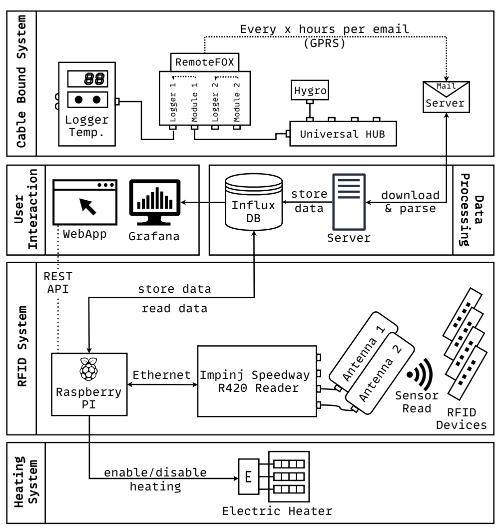


Figure 3: Simplified overview of the monitoring and control infrastructure.

3.1.1 Monitoring Model

The sensor systems (cf. Figure 3) contain sensors for measuring air temperature, humidity, and moisture level of the wall. The cable-bound system periodically transmits the measured data to a processing system. Processing of the cable-bound data is required since the measured data is received in a proprietary format. After processing, the data is stored in a time-series database. To read the measurements of our RFID devices, an Impinj Speedway R420 reader is used. The read sensor data is then directly stored in the time-series database. To monitor the collected data, operators can choose from either using the WebApp (cf. Section 3.3.3) or a Grafana web interface.

3.1.2 Control Model

For the sake of delivering a spike solution for energy efficiency balancing of buildings, the implemented control model for the building's heating system is a simple reactive controller implementing a *sense-evalute-act*-loop. Given a set point temperature that is specified for a room (i.e., the desired room temperature) in the smart building model, we readily generate a corresponding controller which periodically (every 60 secs; this value was established during a set of preliminary test runs as changes of temperature usually are not reflected within time ranges below 60 secs.) evaluates a room's (cf. Section 3.2) temperature against the set point and acts accordingly by turning the heater on/off. Section 3.3.2 discusses twinning and how we embed the controller in detail.

3.2 Smart Building Modelling

As a modeling environment, we used Autodesk Revit 2022. Figure 4a shows a 2D plan of the test rig as used in our work. Specifically, Figure 4a shows the placement of sensors and actuators, e.g., the heater. For our current work, we augment the building model with metadata required by the control model, e.g., the set point for a room's target temperature. For sensors, unique sensor IDs are embedded in the smart building model. For controlling any actuators, we embed information regarding an endpoint (a REST service) together with a list of remote service mappings, each exposing a controllable feature of an actuator in the smart building model.

3.2.1 Test Rig

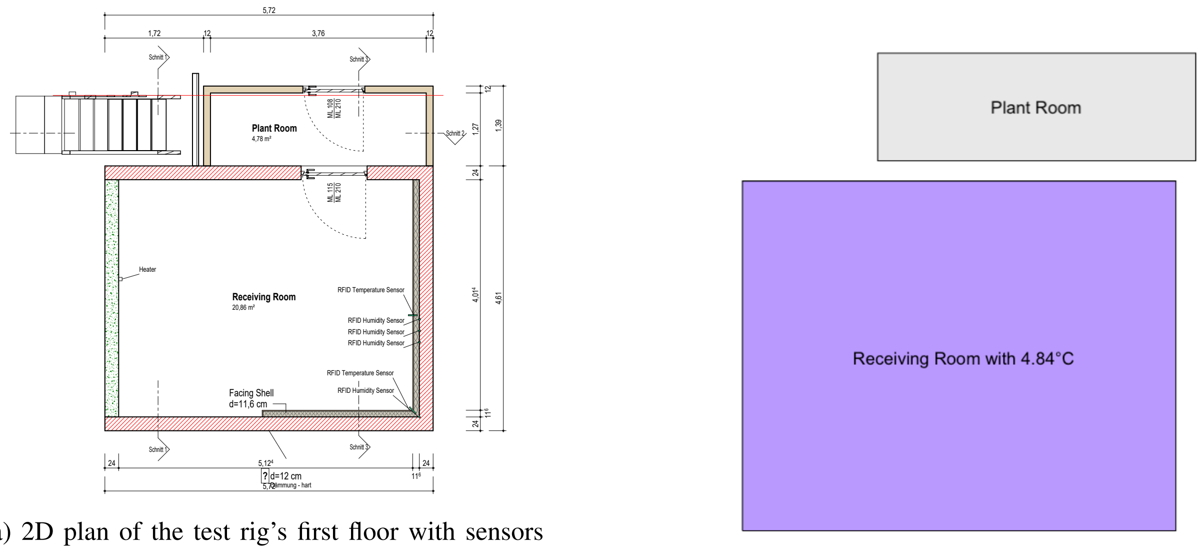
To demonstrate our framework, a test rig equipped with nine RFID and eight wired sensors has been created on a single-room floor of a test stand at the University of Innsbruck (cf. Figure 4a). One RFID device was placed in the room at least half a meter away from each wall. All other RFID and wired sensors were placed within the wall between the insulation layer and concrete. The exact positions for the sensor placement were evaluated in hygrothermal simulations to be the most relevant in terms of the risk of condensation. The RFID sensors were placed at a distance from the wall corresponding to the insulation layer thickness. Two antennas were placed inside the room to gather data from all RFID devices.

3.3 Scalable Digital Twins

Figure 5 shows a procedural outline of our platform for generating DTs. Starting from a smart building model and a database configuration, at first, the virtual instance is generated by a 2D plan of the building (Section 3.3.1). As a second step, given relevant monitoring and control metadata in the building model, our platform automatically twins with the real building (Section 3.3.2). Finally, our environment offers a DT cockpit via a web application for accessing visualizations and data from the building, and a control dashboard (Section 3.3.3).

3.3.1 Virtual Instance Generation

Inspired by the early work of Rasmussen et al. [10], our DT platform receives a building model as its input. Contrary to Rasmussen et al. we however do not employ the BOT ontology [11] for formalizing a smart building model, but instead rely on the IFC, specifically ifcOWL [12], as of its widespread acceptance and better tool support (cf. Section 3.2). At the heart of the virtual instance generation lies *ng-plan* [13], a library



(a) 2D plan of the test rig's first floor with sensors placed.

(b) 2D visualization of the virtual instance.

Figure 4: Building model and 2D visualization of our test rig in our DT platform.

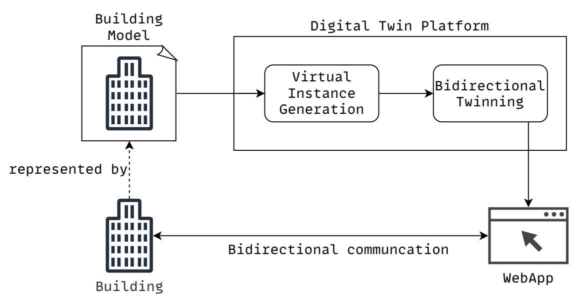


Figure 5: Procedural overview of our platform for DT gestation.

for generating a 2D visualization [11]. ng-plan extracts polygons as text and associates these with rooms to create a 2D visualization [10]. We also extract polygons in a single step by identifying the walls of a room, from which the Cartesian points are extracted and merged into a list, however, from a model formalized in ifcOWL. After converting this list to a string representation, it can be fed into ng-plan. Figure 4b shows a 2D visualization of the first floor of our test rig (cf. Figure 4a).

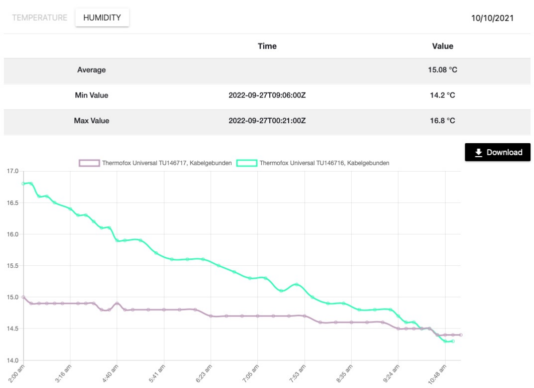
3.3.2 Bidirectional Twinning

Our DT platform is capable of bidirectional twinning with the CPS by extracting information embedded in the smart building model (cf. Section 3.2). For sensors, we extract sensor IDs from the building model using SPARQL queries. Roughly spoken, we filter out any sensor IDs from any rooms in the building to subsequently generate SQL queries for extracting sensor data from the time-series database which needs to be configured as part of the twinning process. As a proof-of-concept, in this work we investigate the automated twinning of switching devices as actuators, e.g., on/off relays for controlling the heater (cf. Figure 3). We extract a service endpoint together with existing service definitions (cf. Section 3.2) which we map on a control UI element in the dashboard (cf. Figure 6b).

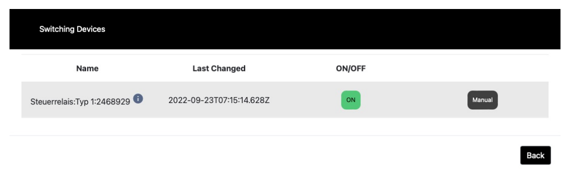
During twinning, our platform allows instantiating a predefined control model (cf. Section 3.1.2) for, e.g., the heater. Currently, we provide code-based extension points using the Strategy Pattern [14]. The extensibility provided by the Strategy Pattern readily allows for implementing custom, more advanced controllers as part of future work.

3.3.3 Digital Twin Cockpit

Our DT platform provides a DT cockpit by a web application (cf. Figure 3). Its entry point is the 2D visualization of the building's rooms (cf. Figure 4b). By clicking on interactive rooms, e.g., *Recieving Room* (cf. Figure 4b), the user opens monitoring and control dashboards (cf., Figure 6). From the monitoring dashboard (Figure 6a), current and historic sensor readings can be visualized and extracted for further analysis. The control dashboard (Figure 6b) allows to (besides automated control) manually control available switching devices in the building, i.e., the heating system as depicted in Figure 3.



(a) Monitoring dashboard.



(b) Control dashboard.

Figure 6: Monitoring and control dashboards.

3.4 Summary of Contribution

Figure 2 shows a holistic and procedural overview of our environment for scalable building energy efficiency balancing as introduced in the previous sections. With smart building modeling as a prerequisite for specifying the CPS, and energy efficiency balancing as an application, our DT platform creates an innovative data cycle for monitoring and controlling a building to balance its energy efficiency. Feedback from experimentation is fused back into the specification of the CPS whereas monitoring and control allow for achieving compliance with energy efficiency balancing requirements. The proposed environment thus transfers the principles of energy efficiency balancing to the planning and design, and the operation phase of smart buildings. Our contribution is available for download at https://github.com/phizech/SensorBIM.

4 EVALUATION

In evaluating our treatment for energy efficiency balancing, in line with DSR, our focus is on (i) treatment completeness relative the to motivating application, i.e., building energy efficiency balancing (cf. Section 2), and (ii) the validity of our treatment and the implications it has on building energy efficiency balancing, and – in a larger context – BIM2BEM.

4.1 Methods

Our evaluation is split into two parts. Firstly, we investigate the completeness of our treatment w.r.t. the requirements from Section 2 (Section 4.1.1). Secondly, we conduct questionnaires with experts to assess the validity of our treatment and its implications (Section 4.1.2).

4.1.1 Treatment Completeness

Our platform delivers [R1] (cf. Table 1) by its high degree of automation [R11] and its reliance on a single unified model [R4] for instantiating a DT. This readily delivers reusability [R2] as a DT can be instantiated simply by feeding a SUM of a building into our platform (cf. Section 3.3). We thus also deliver [R4]. As for energy efficiency [R3], the RFID sensors keep energy consumption low as of no need for a constant energy supply like for the wired sensors used in the test rig. The energy consumption (calculated over a year) resulting from the querying of the RFID sensors in the test rig is about 4.7 kW h for an hourly query. As a boundary condition, the power consumption of the active UHF RFID reader is 16.1 W. In direct comparison to the cable-bound sensors in the test rig, which are not based on ultra-low power, the annual energy costs are negligible.

Our platform supports the visualization of historic and real-time sensor readings [R5] by its DT cockpit [R9] (cf. Figure 6a). [R6] is delivered by enabling users to download historic data in the form of CSV files for further investigation. By implementing the Strategy Pattern (cf. Section 3.3.2) our platform provides the necessary extension points for an extensible controller API [R7]. Remote control of a smart building is delivered as part of the twinning process (cf. Section 3.3.2) [R8]. In addition, our twinning process provides the needed interoperability [R10] for bidirectional communication. Our platform is highly automated thus delivering automated deployment of DTs from a SUM [R11]. For our test rig, deployment times vary around approx. 41 seconds (+/-1sec) on a Lenovo laptop running an Intel i7550@2.5Ghz with 16 GBs of RAM. Our platform thus delivers a fully functional DT from a smart building model within less than a minute, again emphasizing scalability [R1]. Finally, our resulting treatment is pervasive [R12] as the building-side monitoring infrastructure, e.g., the RFID sensors, are placed inside the wall as early as during the construction phase, and thus not visible to any occupants. The computing infrastructure is hosted remotely. We ignore any wired sensors, as these are only for reference. We also ignore the visible stationary RFID antenna system used during our experiments which during operation in production is not necessary.

4.1.2 Questionnaire

An expert survey was conducted to assess the practical applicability and functionality of our DT platform. Fourteen experts (general contractors, designers, energy planners, house management) were interrogated subsequent to a concise exposition encompassing the concept and technical implementation of our platform. Regarding BIM2BEM and automated energy efficiency balancing, the initial two questions elucidated the current state of the art within the organizations/companies of the invited experts. In the majority of cases (8 out of 14), no BIM2BEM-workflow has been established to date; in 5 cases, a BIM2BEM-workflow is currently being developed; and in a single case, BIM2BEM is already being utilized in some cases. Without exception, no organization has a completely operational BIM2BEM-workflow despite pointing out its necessity.

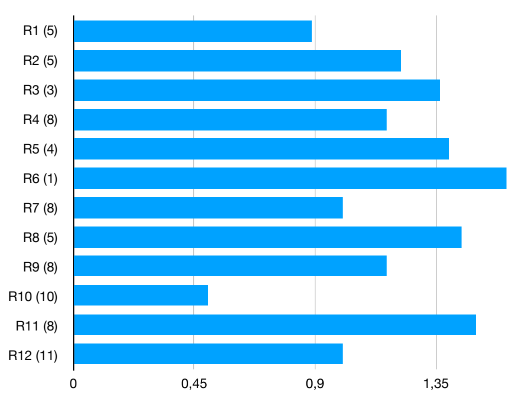
Following these general introductory questions, the specific DT platform was evaluated in terms of its practical use. The highest benefit was found in the operation phase (40%) and planning phase (35%) whereas the commissioning phase was rated only with 25%. The highest benefit was expected in the case of new buildings (63%) compared to refurbishing (37%). Figure 7b shows the types of buildings that are expected to benefit the most.

The highest saving potential is expected to be found in the operation phase (73%) compared to the planning phase (27%). Within the operation phase, the highest practical use was seen for facility management as well as control (each 32%), whereas troubleshooting (26%) and others (11%) were rated less important. Within the test rig (see Section 3.2.1) sensors were applied for the measurement of temperature and humidity. Temperature sensors, mostly for control of heating or cooling as well as humidity sensors (especially for detection of moisture damage) were rated as most important (42% and 38%, respectively). Light sensors were rated with minor importance (8%) as well as 13% other use cases. Besides the availability of DT platforms, several other hurdles were identified by the experts as shown in Table 2.

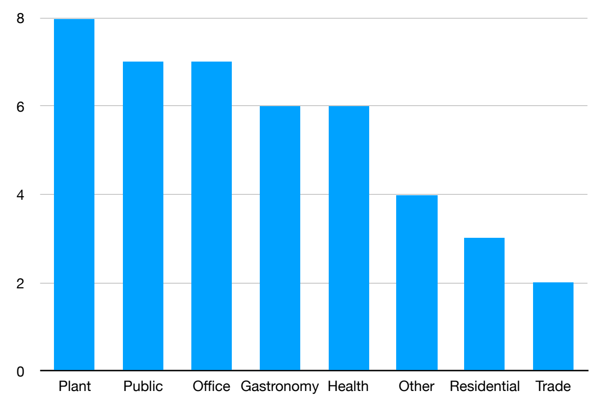
Table 2: Current issues in implementing BIM2BEM (numbers in brackets denote mentions).

Contract design and liabilities (1)	Market/industry is not ready yet (1)
Responsibilities and fee regulation (1)	(CA)FM is not yet widespread (1)
Overlapping implementations among different planning phases (1)	Data protection (3)
Planning culture (1)	Data as a contractual basis, especially in Austria (1)
Use of digital data as a basis for contracts (1)	Not yet really accepted by planners and users (1)
Not yet arrived in the world of planning (1)	

During our expert interviews, we also asked the participants to evaluate the list of requirements (cf. Table 1) regarding (i) necessity, and (ii) deliverance. We, therefore, provided a Likert scale ranging from -2 to 2 (with steps of size 1). In case an expert lacked the necessary background to meaningfully reply to our question, we offered the possibility of abstention by voting with 0. The mean for each answer was then calculated by diving the total sum of votes by the number of replies, i.e., 14 (total number of participants) minus the number of abstentions. Figure 7a shows the results for [R1]-[R12] with abstentions denoted in brackets. We argue that both the elicited requirements are relevant for a DT platform for energy efficiency



(a) Approval and deliverance rating (mean, see text for description) for the requirements from Table 1.



(b) Types of buildings that are expected to benefit the most from our platform.

Figure 7: Results from our questionnaire.

balancing of buildings and that they indeed were appropriately delivered, except for [R10] and [R12]. In retrospect of our test rig and the demonstrated spike solution, there is not much interoperability in the sense of, e.g., communicating with 3rd party services. However, our spike solution demonstrates that our platform supports different communication protocols (REST for control, CollectD for data collection, Line protocol for writing data, HTTP for querying data) by allowing distinct systems to communicate with each other. In the event of [R12], survey participants did not get the chance to physically examine our test rig, resulting in abstentions. However, capitalizing on wall-embedded RFID sensors, our solution is pervasive by not leaving any visible marks. Again, the cable-bound system is neglected at this point as it is only for reference to ensure that measured values are correct. Thus, we argue that our results align with our discussions from Secs. 2 and 4.1.1 by endorsing our treatment.

4.2 Related Work

Building automation has received a lot of attention over recent years [15–17]. Especially energy balancing of buildings is a rapidly developing discipline [18, 19], as of its relevance for climate protection [20]. This is reflected in national, European, and international goals and requirements (cf. European Green Deal), and the standards and regulations derived thereof [21]. So far, quality assurance has mainly been related to building operation [22–24] by a posteriori refurbishments [25, 26], but not to the planning and design phases. Specifically, existing works address the placement of sensor networks [22, 23] and data mining [24] for energy efficiency balancing in existing buildings thereby failing to deliver an integrated approach where sensor placement and accompanying development of control strategies are already considered during the planning and design phase which is crucial for meeting operation goals [27]. Against this background, the need for an integrated DT platform for energy efficiency balancing from planning and design to the operation phase, whose feasibility has been demonstrated by our spike solution, becomes obvious. Our contribution stands out due to its full integration which has not been achieved previously [20] and advances from related work in that the linking of DT and control strategy with the building is fully automated and the resulting communication infrastructure works bidirectionally.

The fusion of BIM and RFID is not novel [28]. The representation in the BIM model is not only limited to the location and geometry (bounding box and exact sensor position) but also reflects sensor and actuator data, as well as metadata relevant for a control strategy (cf. reactive control and the corresponding set point, Secs. 3.3.2 and 3.1). These are not only used for documentation and visualization but are directly and operationally linked to the control strategy. In combination with climate data and weather forecasts, even model predictive control can be used to increase savings on energy bills [29].

The topic of automated DT cockpit generation has not received much attention so far. Except for the works of Dalibor et al. [30] and Bano et al. [31] we are not aware of any other framework for the automated synthesis of a DT cockpit. Contrary to our approach where existing models are employed (e.g., IFC), Dalibor et al., but also the work of Bano et al. introduce additional layers of abstraction and overhead by requiring dedicated modeling of the DT cockpit [32] instead of employing already existing models.

4.3 Threats to Validity

This section focuses on the main issues that may undermine the validity of our study and the methods we used to reduce their influence, as outlined by Wieringa [7].

Construct validity affects both *artifact construction* and *operationalization of constructs*. For constructing our artifact, we followed an established research approach - DSR - to drive artifact design. In the course of this, we employed multiple actions to assure construct validity, viz. the meticulous inference and definition of the artifact, prototyping and piloting and eventually conducted expert interviews.

Internal validity refers to the extent to which the observed effects or outcomes in a study may be attributed to the design of the objects or interventions, rather than additional external factors. Our assessment indicates that it is possible to improve cooperation between different fields and automatically generate DTs for building energy efficiency balancing processes. Nevertheless, our analysis has been limited to a singular setting only. To enhance the strength of the evidence, it is imperative to assess our proposal in different settings. Consequently, we aim to evaluate additional settings after our prototype reaches TRL6. Furthermore, during this process, we will reassess our proposal using the Technology Acceptance Model (TAM).

External validity pertains to the degree to which the results of a research study can be extended and utilized in many settings. We acknowledge that our contribution was solely assessed in one setting. To mitigate this hazard, one potential approach is to employ alternate settings. By doing so, we can authenticate the outcomes of our research. There is no reason to presume that our contribution cannot be applied to further settings.

5 CONCLUSION

In our paper we have introduced a novel approach to automated DT generation using smart building models on top of the IFC. Our results show both the practical feasibility and the applicability of our framework for remote monitoring and control of physical buildings. Our work substantially advances the design of energy-efficient buildings by making a leap towards devising an optimal control strategy for buildings by linking BIM, IoT, sensors, and actuators. Due to [R1] (scalability) and [R2] (reusability), our treatment can be used for almost all types of buildings (cf. Figure 7b) with no limitation on use, size and complexity. Even scaling up to entire districts would be conceivable, as the overall platform is optimized for processing high data rates.

Within several expert interviews, our platform was evaluated in terms of meeting the requirements (cf. Table 1). All requirements were met without exception. The general idea of automated energy balancing using a DT cockpit was estimated as highly interesting, both for new buildings and refurbishments. In many companies, however, the requirements w.r.t. BIM2BEM have not yet been established or are only in preparation. For a broad application in the future, the experts see fewer technical problems than contractual ones. The workflow and planning process at the moment is divided into two parts, the preliminary planning, and the implementation planning. With the workflow proposed in this work, the implementation planning could take place already in the early planning phase, as the control strategies as well as sensor placements, parameters, and set points can be tested in a dynamic simulation before the rollout in the real building.

Further applications and developments in CAFM are conceivable, especially for automatic error detection and troubleshooting in automated building control. In this case, a simulation model, which was used for testing the control strategies in the planning phase, can also be used in the operating phase. If the simulation results are compared with the measured data in real-time, any serious deviation can be interpreted as an indication of a malfunction.

ACKNOWLEDGEMENTS

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