Digital Twin as energy management tool through IoT and BIM data integration

Alice Schweigkofler [a], *Orjola* Braholli [a], *Sylvia* Akro [b], *Dietmar* Siegele [a], *Paola* Penna [a], *Carmen* Marcher [a], *Lavinia* Tagliabue [c], *Dominik* Matt [d].

[a] Fraunhofer Italia, Via A. Volta 13 A, 39100 Bolzano, Italy, alice.schweigkofler@fraunhofer.it

[b] Dipartimento ABC, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano MI, Italy

[c] Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, University of Turin, Via G.Verdi, 8, 10124 Torino, Italy

[d] Free University of Bozen-Bolzano, Piazza Università 5, 39100 Bolzano, Italy

Abstract. Energy Management has gained increasing value in construction market. The spread of Building Information Modelling (BIM) as a methodology for the construction processes organization will bring progressively to a digitalized asset management. Taking a step further, the concept of Digital Twin (DT) is being used to integrate building's assets with digital technologies to allow real-time analysis, as well as to provide simulation capabilities. DT is expected to have high impact on facilitating sustainable transition through technological developments, according to the European Green Deal mission. Considering operation and maintenance phase in building lifecycle, one of the main problems is about data management. Energy managers and decision-makers use indeed text and spreadsheets to visualize and interpret data. The most recent software solutions in this field focus mostly on the collection of information in a systematic way and in document and deadlines management. This approach helps operators but makes it difficult to understand the real-time building's performance. Furthermore, the indoor environmental performance in dynamic use conditions is rarely considered in decision processes. Therefore, a more efficient and less error-prone method is needed for the real-time management of heterogeneous data. A new approach which combines BIM and Internet of Things (IoT) technology could create a shared data environment for crossed management energy aspects. Equipping the building with monitoring systems means that a large amount of collectible data needs to be managed. This paper describes an attempt to represent and visualize sensor data in BIM, in a user-friendly way to support complex decisions as a significantly improved alternative compared to the traditional ways. The proposed framework is tested and verified on the case study of a school building within the project "SINCRO". In the first part of the paper the use case, devices, and the proposed BIM-IoT integration workflow are described. In the second part the resulting cloud-based DT is explained together with its functionalities applied to a testing period. Feedbacks of the energy manager are collected to demonstrate how real-time performance information can lead to more responsive building management and improve energy efficiency.

Keywords. Digital Twin, BIM, IoT monitoring, Energy Management, Indoor thermal comfort.
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1. Introduction

Real-time energy evaluation and management of a building is the key to achieve efficient and sustainable buildings [1]. Moreover, making available a high quantity of data on energy consumptions and indoor conditions of an existing building can have various positive impacts, i.e. it can drive the choice of energy retrofit interventions [2]. Considering public wellbeing, monitoring the Indoor Environment Quality (IEQ) in real-time is particularly beneficial for health-purposes. Indeed, indoor air pollution has been ranked among the top five environmental risks to public health [3] and from a survey conducted on US consumers, 76% would feel more comfortable entering buildings where IEQ is monitored and known.

Within the entire building lifecycle, the Operation and Maintenance (O&M) phase is the longest period [4] and thus it is also the most expensive phase. Therefore, efficiency and optimization in information management during building utilization is becoming essential. It more and more helps managers and maintainers to have a clear picture of buildings health. A monitoring system established to check the internal environment can be very helpful and beneficial to ensure that buildings remain in good condition [5]. Moreover, it can be helpful for in-time decision-making or strategy changing that requires real-time data about building performances and energy management [6]. Despite this, at the moment the implementation of digital information management is not widespread [7].

To address this growing need, it is important to provide an appropriate method for sensor data visualization, as it may help building managers and/or users to intuitively understand and work with data faster and easier [2]. Technology such as the Internet of Things (IoT) is increasingly being deployed in the built environment to monitor building performance. Combining IoT with Building Information Modeling (BIM) methodology would make it possible to transform the interaction with the built environment. The integration of BIM with real-time data from the IoT devices result in the creation of Digital Twins (DT). This development is quite in an early stage, but it is already a powerful paradigm for numerous applications to increase construction and operational efficiencies, thanks to improving information availability. According to this, the overall purpose of this research is to integrate and visualize real-time and indoor monitoring sensor data during the building's lifecycle, with a special focus on energy management. The aim is to display a decision-making dashboard of indoor thermal comfort to support complex decisions, in a user-friendly and immediate way. Such a DT is presented as a significantly improved alternative compared to traditional ways for information management in O&M.

The paper is organized as follows. In section 2 it is presented the state of the art in the scientific field. Section 3 exposes the methodology and tools employed to integrate BIM and IoT and data within a unique and replicable workflow of the system. Moreover, a case study is presented. Results in terms of data visualization are presented in Section 4 and conclusions are presented in Section 5 and 6.

2. Background and state of art

During the O&M period of buildings the environment information should be constantly monitored to allow supervisors to take measures, deal with emergencies and improve energy efficiency. Nevertheless, building managers and decision-makers still face the need for solutions that allow to visualize, interpret, and utilize data [8]. They currently still use text or spreadsheets, which make it difficult to understand and to track the real-time building's performance, as well as this is a prone to errors way of work. [9]. Therefore a faster, more efficient and less error-prone method is needed for the real-time visualization and analysis of collected data. There should be a monitoring system, which can alert people under certain circumstances [5]. Our study shows how BIM-sensor integration can lead to more responsive building management and operation by making indoor condition data tangible and accessible for property managers, owners, and occupants within a user-friendly digital system.

2.1 BIM in Operation and Maintenance

Many studies have tried to review the status quo of BIM applications in building operation phase. Most studies were related to the design and construction stages, while few concern building maintenance, retrofitting, and demolition stages [10]. Generally, recent analyses [11] evaluated and summarized that BIM for O&M phase is still in its early stage. In particular, the use of BIM only as a three-dimensional model has no added value in the O&M phase and the need for interoperability, together with the lack of open systems, discourages its use. Moreover, the information contained in BIM models is static, while building maintenance requires dynamic data which include real time information. In the usual practice, a large amount of data can be provided, but these are not updated during the building life cycle. This lack of data and information in as-built digital models considerably limits the potential of BIM in building management [12]. Despite this, BIM is an important factor in improving decision making for buildings throughout their life cycle. For example, in [8] an exhaustive list of specific BIM functionalities in O&M is provided. It includes controlling lifecycle cost data and environmental data, locating building components effectively, facilitating retrieval of real time integrated building, improving maintainability studies and space management.

2.2 Digital Twin as BIM and IoT integration

BIM-IoT integration takes advantage of the geometric and parametric properties of BIM models and of the real-time streaming of environmental data (e.g., temperature, humidity, etc.) collected by IoT sensors, to create a DT for visualization monitoring data in real-time. This is a new approach, that integrates BIM data with sensors to create a shared database for improving the building's energy and indoor environmental performance, while reducing operational costs [9]. In this way, BIM technology can effectively cope with the complexity of the O&M of buildings, if it is coupled with monitoring data. In a BIM based building monitoring system, data can be classified into two categories: environmental data and BIM data [5]. The monitoring data are a kind of timeseries data produced by working sensors and the BIM data consists of a variety of information about building components. Indeed, the combination of BIM and IoT technology provides a comprehensive view of the building status and improves the efficiency of information use [5]. However, research addressing the integration of these two technologies is still very limited and has focused exclusively on the automatic transmission of sensor information to BIM models [13], for example using Dynamo to accept sensor data as input and automatically redraw visualized information in BIM.

A DT has much more potential, since it represents the digital replica of the physical world, where components and processes can be aligned in real-time to achieve greater efficiency and generate a decision-making action. In recent times the application of DT has gained massive popularity in construction industry, while it is already utilized in manufacturing and Product Lifecycle Management. Its idea was already introduced three decades ago [14]. The *buildingSMART International* considers that the concept of DT can be achieved through alignment with common open digital solutions and standards [15].

Most of the definitions agreed on describing DT as the bidirectional data flow in real-time between physical and digital world [14]. In fact, DT is the digital copy of a physical object, and its main elements are the physical space, the digital space, and the bidirectional data flow between them. The evolving profile of a DT achieved from cumulative, real-time data helps to provide important better-decision-making insights on system performance, for example il [16] it has been demonstrated that the improved data management helps in finding some implicit logics among management tasks. What a DT requires is an information system to store building data. This is based on dynamic data, acquired real-time from the building, and on the information of the building itself, which is stored in the model [17].

2.3 Data visualization for energy management

Choosing an appropriate method for sensor data visualization is important as it may help users to intuitively understand and work with data faster and easier [2]. Several studies have been conducted in this direction. A prototype framework for the BIM and IoT-based integration for providing a comprehensive view of the general status of buildings was proposed in [5]. In [2] a tool that can provide building managers with real-time data and information about the energy consumption and the indoor conditions of buildings, but also allows for viewing of the historical sensor data was developed. Machado et al. A novel approach has been proposed in [18] that exploits IoT sensors using Wi-Fi, to evaluate the energy behavior of individuals, which can be applied to identify inefficiencies in individual´s actions and responding to them. In [19] an IoT framework to estimate indoor conditions and occupancy rates, which provided hints for energy-saving strategy by further understanding the indoor condition patterns was proposed. In further experiments, using a cloud-based service, building supervisors can remotely monitor the thermal condition of fan coils and can easily find the location of the faulty component on the building 3D model by room ID or room name [20].

Consequently, all the recent experimentations show that the usefulness of DT in the built environment can significantly increase through the automatic decision making and feedback loops by enabling real-time automated control. It is clear, that this integration method takes advantage of the geometric and parametric properties of BIM models and the real-time streaming of environmental data collected by IoT sensors to create a DT for visualization monitoring data in real-time. However, despite the emerging new data capturing technologies and advanced modelling systems, the process of DT modelling for existing buildings still lacks a systematic framework [21].

3. Methodology

Our research proposes a scalable and flexible workflow for creating a cloud-based and accessible solution, that enables BIM-IoT integration in a DT. A case study was used to test the framework implementation. The developed methodology for integrating the monitoring data with BIM was tested on an existing school building located in the South Tyrol province of Northern Italy. The building has a total area of approximative 1450 sqm, two floors and a vast number of spaces for different uses like teaching classes, playing areas, kitchen and offices.

3.1 Energy monitoring

For this study, there were two types of implementation domains: IEQ and indoor thermal comfort. IEQ refers to the quality of a building's environment relating to the health and wellbeing of users. IEQ parameters were measured such as temperature, humidity, CO_2 concentration, Total Volatile Organic Compound Concentration (TVOC) and illumination. Indoor thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment" [23]. This condition can be expressed by the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices, which are the most widely used thermal model for indoor environments [22], adopted by many international standards, such as ISO 7730, ASHRAE 55 [23].

Multiple market-available sensor devices were deployed in the indoor spaces of the school building to perform environmental data collection. The IEQ parameters (temperature, humidity, CO_2 concentration, TVOC and illumination) were measured for each room. Data are gathering each 10 minutes. The indoor thermal comfort parameters (PMV and PPD) are calculated for each classroom i.e., for each room for which advanced monitoring is planned. The sensor fleet is comprised of four sensor types and of twenty-four instances placed in total in the building.

Figure 1 shows where the sensors are located on the ground floor and how the different areas are monitored. Except for one of the classrooms, where five sensors are installed measuring all the parameters mentioned before, all the classes have been equipped with a sensor which is integrated with an additional display. This is classified as advanced monitoring. All the other rooms i.e., two offices, one kitchen and the corridors are classified under basic monitoring, where one sensor is installed without a display. Service areas were not monitored. The first floor is composed about only one class, where advanced monitoring is performed.

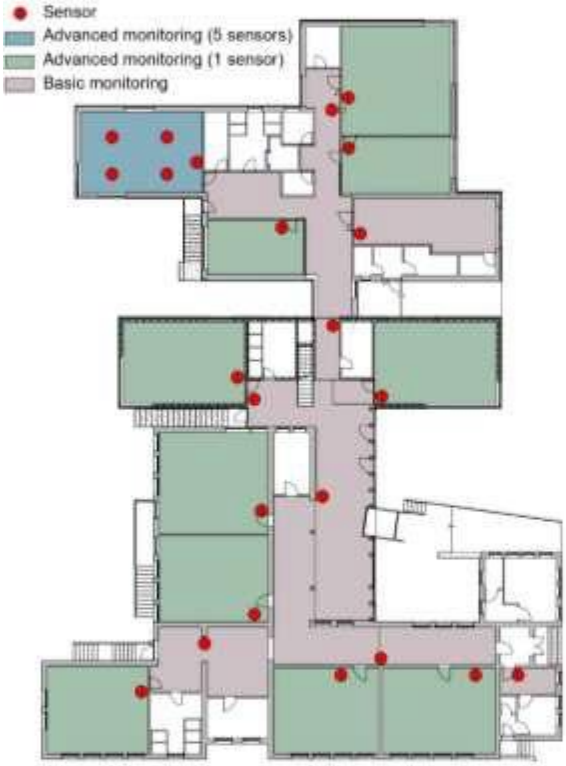

Fig. 1 – Monitoring system and sensor deployment on the ground floor.

3.2 BIM model

The BIM model of the school building is built within a BIM environment using all the information from the existing documentation. Revit 2020 software was used to develop the model throughout the whole modelling process. Figure 2 shows the general view of the BIM model. The level of information needed is such as to provide an accurate geometrical representation of the building's existing state and accurate positioning of the sensor families in the building. The geometrical information is represented mainly on a generic level with some elements represented in a more detailed level like sensors, walls and windows. The advantage of the BIM environment is that it provides the possibility to integrate different types of information in a single model. E.g., the sensor family contains information regarding the identification and environmental parameters that are mapped and connected to the real-time data in the DT.

Fig. 2 – Overview of the school building in the BIM model.

3.3 Integration of sensors in the BIM model

A unique family was created as a generic model to represent all the sensor devices. This sensor family was placed in the BIM model representing the real position of the asset in the physical building, as shown in Figure 3. The different sensor devices installed in the school building were created as types under the sensor family with varying type and instance properties. Two sets of parameters were created for the sensor family and grouped under Identity Data and Green Building Properties. The Identity Data is an existing section in the Type Properties window that contains identification parameters of the family type. In this case it contains parameters for the name, location and activation state of the sensor. Green Building Properties is a created section in the Type Properties Revit window that contains the environmental parameters measured by the sensors. Each virtual sensor placed in the model is defined as a unique alphanumeric ID which derives directly and corresponds to the location where it is placed, i.e., the ID contains the building zone, floor number and room number and it is automatically generated. In this way the sensors are correctly mapped in a unique way.

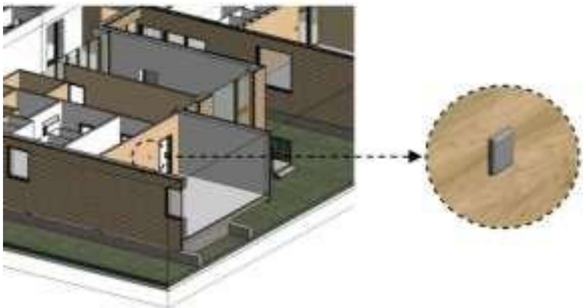

Fig. 3 - The sensor family.

The Green Building Properties represent all the environmental parameters that the sensor is measuring inside the building (Figure 4). Each of these parameters is mapped and connected within the DT with the respective sensor values.

Fig. 4 - Sensor type example ELSYS ERS-CO2.

3.4 BIM-DT workflow

This paragraph describes the detailed application of the proposed workflow from the data collection process to the output visualization in the DT. Figure 5 shows the workflow schema made up of four main layers starting from the physical asset to the digital asset. The four phases from data acquisition to data analysis are described below.

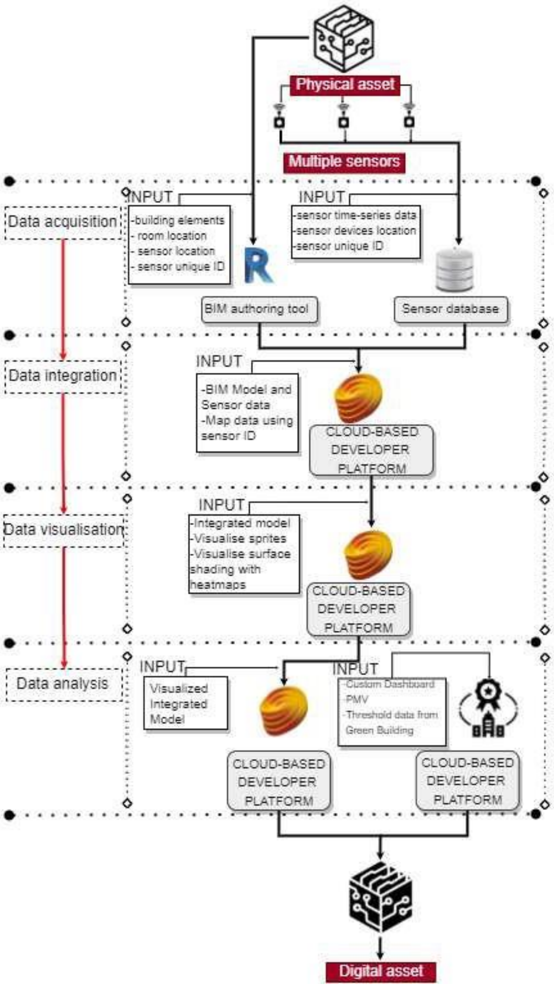

Fig. 5 - BIM-DT workflow process of implementation.

The first phase is about "data acquisition". The input data for the DT are obtained from two sources. The first source is the BIM model of the school building from which are obtained the geometrical information, the location of the virtual sensors accurately positioned in the model, their unique ID and their Green Building Parameters. The second source is the indoor environmental data retrieved from the IoT sensors in the building. The real-time data obtained from the sensors are stored using an InfluxDB database, a type of database developed specifically for storing time-series data.

The second phase is "data integration" and consists of matching the properties of the sensor data parameters with the sensor family parameters, previously created in the BIM model. A dynamic data integration process between BIM and IoT has been created, mapping and connecting the sensor data from the InfluxDB database to the sensor family in a cloud-based integrated model, using Autodesk Forge Platform. This is a cloud-based platform and provides Application Programming Interface (API) services that enables developing customized and scalable solutions to solve design, engineering, and manufacturing challenges. Forge APIs is partially and temporary available in open-source mode. It provides the necessary and sufficient services to create the customized application [20]. Most of the process to set up the DT was done in Visual Studio Code.

In the data visualization phase Autodesk Forge Platform is used to visualize the outputs that combine the BIM model and its data to the environmental data retrieved from the sensors. This is where the user interacts with the application. The platform itself is web-based and can be use in any web browser. It is obtained in this way, the visualization of contextual and spatial information in real-time. The resulting dashboard is further explained in section 4.

In the data analysis phase, the indoor environmental data retrieved from the IoT sensors are analyzed and compared with environmental data thresholds and ideal indoor thermal comfort conditions. Comfortable values have been defined according to Table 1 in concordance with green building benchmark standards.

Tab. 1 - Comfortable values for monitored parameters.

Temperature	Winter between 20 – 25°C, while summer between 23 – 26°C
Humidity	40 – 70% [24]
CO2	400 – 1000 ppm (CEN, EN 13779)
TVOC	300 – 500 ppb [27]
Illumination	100 – 500 lux (UNI EN

	12464:1:2004)
PMV	Between -0.5 and 0.5 (ISO 7730)
PPD	Below 10%

4. Results

The resulting application is a cloud-based dashboard where the user can interact with the DT of the school building. It is possible to deploy this DT to be viewed on the browser for easy accessibility from anywhere. The system is active since February 2020 and the project is still ongoing. In Figure 6 the dashboard is shown, and the functionalities are explained in this section.

Fig. 6 – Digital Twin and surface shading map.

BIM model: the BIM model can easily be explored and interrogated through the toolbar, including the parameters of single objects, such as walls, windows, doors, etc. The model is sectioned to allow internal view of the building.

Sensor visualization: grey dots as two-dimensional objects are overlaid onto the model to highlight and indicate sensors. This was done by using the location of the device family in the BIM model. A developed function checks the model and finds elements with the unique alphanumeric ID. It is possible to click on the dots to visualize every actual measured values. In the right side of the viewer the sensor list is placed, where every sensor can be found, and graphs on historic values can be checked.

Color map: every classroom is characterized by a colored surface shading, which is a graphical representation of the values measured in each room. Every monitored parameter (temperature, humidity, CO_2, TVOC and illumination) can be chosen from a drop-down menu, to be visualized in the DT. The calculated thermal comfort level (PMV and PPV) is visualized in the DT in the same way. To generate this map, based on the position and size of each classroom, a bounding box is obtained, and sensors have been linked to them. This step can be done automatically since room information and device position are available from the BIM model.

Gradient: the color assigned to the surface shading refers to the output of data analysis. The visualized color depends on minimum range and maximum range value and varies between a multi-colored gradient for each monitored parameter. The information about the device type is used together with the specific gradient for creating the surface shading of the classrooms. Moreover, to make sense of this data for the user, a legend has been added to compare measured values and map colors to green building benchmark standards.

Data: through the time slider placed in the upper part of the viewer, it is possible to not only display the real-time data from the building, but also to visualize data of the past. To add the sensor data from the InfluxDB in real-time, this is done creating a custom data adapter and gateway. It is possible to use a time-series data source for the visualization of historic data over a specific timeframe. This option has been explored using a CSV file for a timeframe from June to July to analyze in detail the summer season.

5. Discussion

In order to compare the proposed DT as new representation of data with the actual situation, the system has been presented to the supervisors and energy manager of the school building. Thanks to the received feedback it has been confirmed that the color map for the intuitive interpretation of data makes the DT more user-friendly. The end-user can easily evaluate the thermal comfort level in real-time for decision making. Moreover, the proposed visualization dashboard can be used and understood by anyone with a less technical background. It allows users to interpret values immediately rather than the usual way, such as using bar diagrams, tables, and graphs. Moreover, this kind of representation induces user commitment and increases user engagement and participation in taking actions for comfort improvement. Since the energy manager is not usually the BIM model author and does not have access to BIM authoring software, it has been appreciated that the application is easily accessible through a browser. The proposed workflow is cloud-based and in addition it can integrate BIM models from open non-proprietary file formats such as IFC, gbXML, glTF as well as other industry proprietary file formats. However, the selected case study is a medium-small sized building and there are no historical data available about energy management of the building for a quantitative comparison after adoption of the system. Neither a BIM model of the building was utilized, and the detection of energetic anomalies and discomfort was previously not carried out. After a certain period of use of the DT it will be possible to estimate the usefulness of the system on the basis of the number of anomalies detected, with the aim to perform an evaluation of application of the technology.

A limitation in the proposed approach is that a small number of sensors were used to test the proposed framework in this study. As the system evolves and the amount of data increases, it will be necessary to implement a data analysis module to manage and detect data anomalies, possibly based on artificial intelligence. Moreover, only indoor environmental monitoring has been performed. This could be extended integrating information about building energy simulation and/or the monitoring of building facilities for evaluating energy consumptions. To view such kind of information could have high impact in improving energy manager´s work. For this study, it is planned to monitor the heating system, that is connected to district heating system, partially with traditional radiators and partially with underfloor heating. Except a mechanical ventilation system located only in four classrooms, the building is not equipped with other kind of plants or automation system. Further, the BIM model could be enriched with energy parameters of components. Through a cross-analysis of the proposed data collection the DT could suggest optimized management strategies and indicate limits beyond which renovation interventions would be suitable. Further research and improvement on the workflow implementation could focus on predictions and on automatic control feedbacks. Predictions can be performed through advanced data analysis to provide better insights and evaluation, allowing for predictive energy strategies. On the other hand, defining an alert system to notify unacceptable threshold of monitored parameters, could lead to quicker response and fast reactions.

6. Conclusion

The implemented framework integrates the indoor environment data collected by multiple sensors with a BIM-based model to automatically combine monitored data. The followed workflow is based on a four-layer methodology, which are data acquisition, data integration, data visualization and data analysis and can be adopted for further monitoring system implementation and extension. The real-time visualization of indoor environment conditions provides a better overview of the building status to supervisors. As a result, it plays an important role in increasing commitment in taking improvement actions for indoor comfort and in engaging users to accept building interventions. It has been confirmed by building energy supervisors, that BIM-IoT integration to apply the DT paradigm in the built environment improves the user's experience and better decision-making opportunity and provides useful information to monitor and maintain the building performance during the operational phase, which is the more expensive phase in the whole building lifecycle. To promote openness and interoperability between disciplines and different BIM authoring platforms used in the building industry, Autodesk Forge was used as cloud-based developer's platform to create the DT based on its capability to integrate models from open non-proprietary file formats as well as other industry proprietary file formats to visualize indoor monitoring data. Despite the acquired benefits, the application of the DT paradigm in the construction industry has still enormous potential. An advancement in research in this field, could lead to DTs that support automatic feedback and perform automatic control system in buildings, allowing to automatic actions on built environment according to specific objectives and energy strategies.

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