ISEC 2024 – 3rd International Sustainable Energy Conference
Positive Energy Buildings and Districts
https://doi.org/10.52825/isec.v1i.1154

Published: 18 Apr. 2024

BuildingTwin - Open Platform for Monitoring, Evaluation and Optimization of Building Operation

Andreas Riffnaller-Schiefer[1], and Tobias Weiss[1]

[1] AEE INTEC, Austria

*Correspondence: Andreas Riffnaller-Schiefer, a.riffnaller-schiefer@aee.at

Abstract. Keeping track of all data about a building over its entire life cycle is a major challenge. Planning data, like the building information modeling (BIM) data, is often not carried over into the operational phase. The "as-built" state is commonly documented in various lists and data sheets, independently of the BIM model. And usually neither real-time nor historical data on the operating status of the building is available. This lack of data makes it hard to operate a building in an optimized and efficient manner.

We demonstrate the web-based platform "buildingTwin" to aggregate all building relevant data in a centralized "digital twin" model of the building, combining BIM data from the planning phase, data sheets and attributes documenting the "as-built" state, and real-time measurements from sensors and other sources during the operational phase. This platform provides easy access to all building data and enables monitoring, evaluation, and optimization of the building operation.

Keywords: BIM, IFC, Digital Twin, Sensors, Internet of Things, Visualization, Buildings, Building Operation

1. Introduction

Digital tools are already commonly used during the lifecycle of a building. During the planning phase, a digital model of the building and related planning data, the BIM model, is created. This model is used as the basis to derive plans for the construction process, during which the BIM model may also be enriched with additional data. On the other hand, in the operation phase, CAFM software is used for maintenance management. However, there is typically an information gap between these phases. The planning data from the BIM model is often not used by the CAFM software for building operation. Similarly, maintenance information is not fed back into the BIM model.

Additionally, real-time information about the current state of the building is not easily available, even though many buildings have various sensors and measurement devices installed. But to be able to efficiently operate a building with minimal resources, all this information is crucial.

To enable effective and efficient building operation and to provide all the necessary data, it is crucial to bring together all the relevant information and make it easily accessible. This requires the adaptation of the BIM model from the planning phase for building operation. Additional data such as data sheets and real-time measurements need to be included and continuously updated. A key aspect is to be able to access and update the aggregated data without special BIM software. This enables, for example, contractors to add data sheets and product details to the building data already during the construction phase. The main goal is to provide a detailed overview of all building-related data in an accessible form to enable efficient building operation.

To achieve this goal, we propose a web-based platform, buildingTwin, to collect, manage and retrieve all information of a building in an easy and accessible way. The foundation is the BIM model of the building from the planning phase, which is enriched and updated with additional data, like data sheets and real-time measurements. The web-based platform allows anyone to access this data from any device without requiring special BIM software. This enables low friction contribution of data. For example, executing companies should be able to provide data sheets, product details or warranty information already during the construction phase. The collected information provides a detailed view on all building related data in an accessible way and enables efficient building operation.

2. Related Work

Today, most buildings are equipped with sophisticated building management systems (BMS) that collect data from thousands of endpoints. These systems help building operations managers maintain buildings by minimizing long-term operating costs and increasing the comfort of building occupants. The key challenge here is to collect, structure and analyze the extensive data in a suitable way.

Currently, even in large construction projects, building services are usually only adapted to the expected boundary conditions during the planning phase. Only rarely, i.e. usually when energy consumption values or comfort criteria are not met, is monitoring carried out over a certain period after commissioning (e.g. a heating and/or cooling period, one calendar year, etc.). Based on monitoring results the control system is subsequently adapted to the actual requirements and improved, which, however, involves a considerable amount of time and money.

In the operating phase, key parameters such as energy consumption and user comfort become decisive. The significant deviations from planning values that generally occur are nowadays usually subsumed under the term “performance gap”. The energy performance gap is around 10-15% for near-zero energy buildings in new builds and up to 30% for existing buildings [1], [2], [3], [4], [5].

New digital data processing methods and predictive modelling allow manufacturers and operators of buildings, systems, and components to provide data-based proof of the efficiency of their systems, detect problems and faults at an early stage and derive optimization measures during operation [6], [7], [8]. These methods are often not used because the effort and know-how required for modeling are high. BIM models with information on the physical properties of the building provide an ideal basis for this and could therefore be transferred to operation [9].

During the operation of buildings, CAFM software is typically used by facility managers. But traditionally, CAFM tools did not provide any interfaces to use BIM data for building operation. Only recently has there been work from CAFM software providers to develop interfaces to BIM and to exchange data with BIM systems [10]. While this enables access to information from BIM models during building operation, CAFM software does not provide access to real-time monitoring data from a BMS or other sources.

Web-based platforms to access BIM models have recently emerged as an easy way to access and collaborate on BIM data without requiring special, expensive BIM software. Many commercial web-based BIM platforms are available, but they typically also lack interfaces to real-time building operations data. Platforms that do provide support for timeseries data in BIM models are often based on importing static historical measurements, that can then be visualized together with the building model [11]. However, for effective building operation, access to near real-time measurements is desirable. Historical operations data cannot be used to provide e.g. real-time alerts for out-of-range measurements or adaptive control of building equipment.

3. Implementation

In order to provide users an easy way to access all building related data, the proposed platform is architected as a web application. This enables authorized users to access the platform from any device with a recent web browser, i.e. from desktop computers, notebooks, tablets or even using smartphones. No special software or app is required, besides a web browser, to view and interact with the building model and access all related data.

To facilitate this web-based user interface, the platform is implemented in two major components. First, the back-end application that runs on a web server, providing an HTTP API and all necessary interfaces to authenticate and authorize users and to access all data. These interfaces are used by the second component, the front-end application, which runs in the web browser of the users to visualize the building model and to provide a user interface to interact with all building data. An overview of the complete platform architecture is shown in Figure 1.

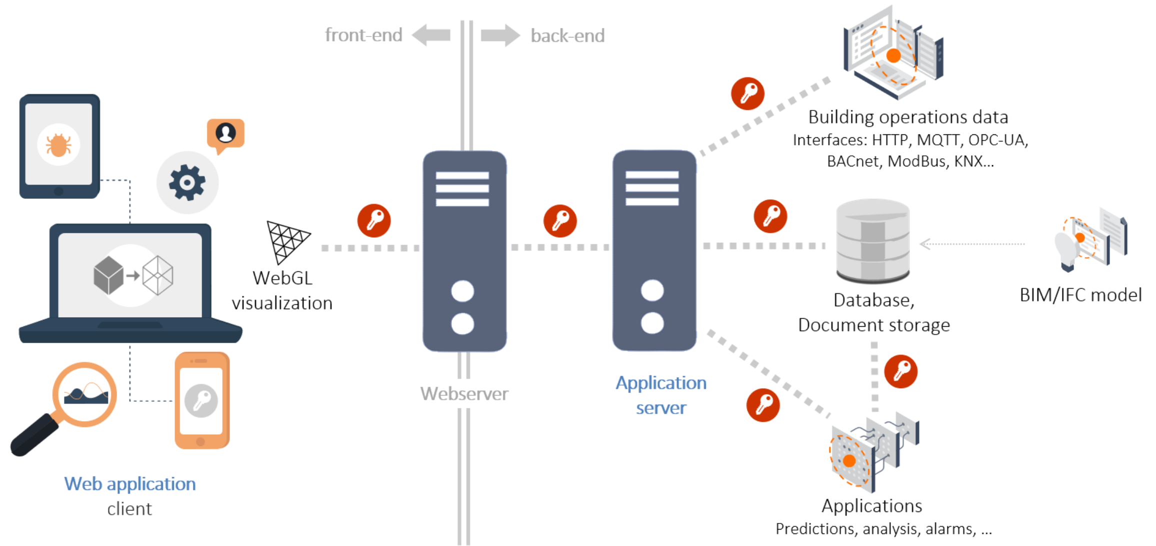

Figure 1. *Overview of the buildingTwin platform architecture. The back-end on the right runs on a web server and connects to services providing building operations data, to databases, and to document storages to manage all building data. Users of the platform can access the web application front-end, shown on the left, using any device with a modern web browser.*

3.1 Back-End

There are many different authoring applications to create BIM models, most of them with their own custom proprietary file format to store and exchange models. However, to support BIM models from any software vendor, the buildingTwin platform is based on the open BIM standard IFC which is a common exchange format between BIM applications of different vendors [12]. Using an open standard ensures that BIM models from any authoring application can be used with the platform, and the platform is not dependent on a particular workflow or software.

On import, the provided IFC models are pre-processed on the server to prepare and optimize them for use in the web front-end application. To reduce the size of the data that needs to be transferred from the back-end to the front-end application when a project is loaded, the data from the IFC BIM model is split into three parts:

- metadata about all building elements, like walls, doors, windows, etc., and about the spatial building structure, i.e. the relations of buildings, building stories, and spaces defined in the BIM model,
- geometry of elements that have a geometric 3D representation, e.g. elements like floors, walls, doors, etc., and
- property and property set definitions and specific attribute values assigned to individual elements for defined properties.

Splitting the data defined in the provided IFC file enables the front-end to only load the data that is required at any point in time. Additionally, the individual parts can be further optimized.

For example, all extracted geometry is stored and transferred using the GLB file format. The GLB format is a standardized binary file format defined in the glTF specification [13] for efficient transmission of 3D models. Several standardized extensions are available for the GLB format to further reduce the size of the data by compressing the 3D model, e.g. with Draco geometry compression [14]. Compared to the text-based IFC format, where files are commonly several hundred MiB large, this minimizes the amount of data that needs to be transferred from the back-end to the front-end for visualization of the 3D building model, and thus reduces loading time for users of the web-based user interface. Figure 2 shows a comparison of the file sizes of several real world IFC models to the size of the extracted geometry in GLB format together with required metadata. Using Draco compression, the resulting file size of the geometry in GLB format can be 50-100x smaller than the original IFC file. Even together with the extracted building metadata, required to visualize the 3D building model, this representation saves a significant amount of storage space and network bandwidth to transfer the data to the front-end application. This is a big advantage compared to other solutions that process the complete BIM project in the front-end.

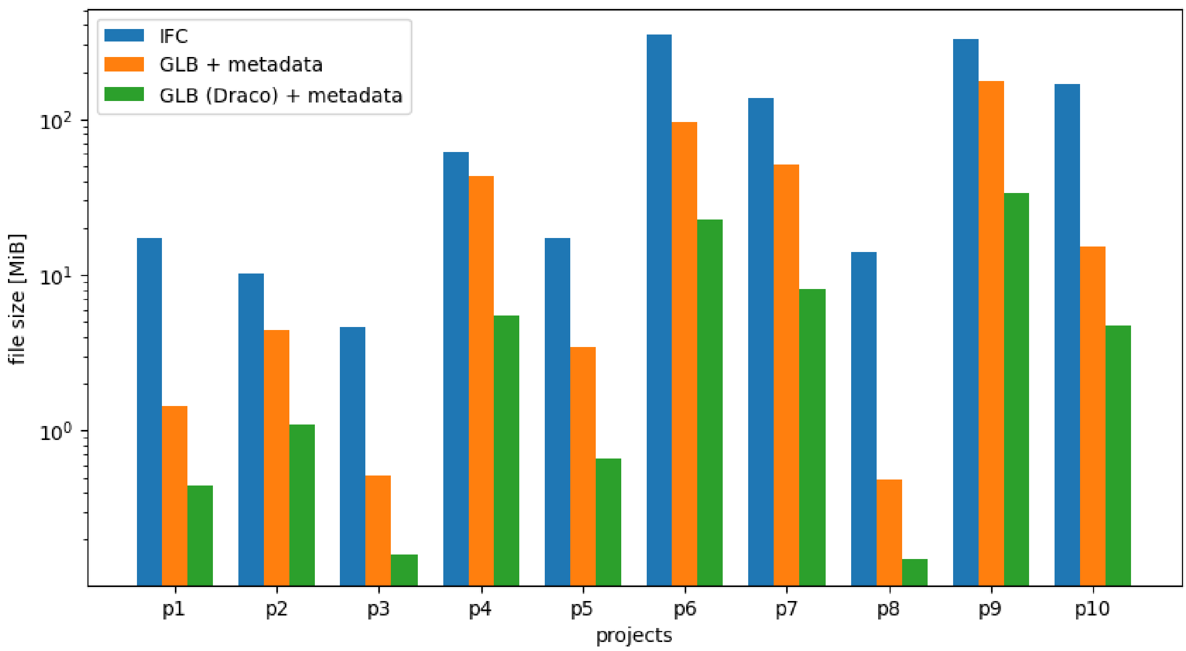

Figure 2. *Comparison of file sizes for 3D building models in different formats (log scale). The source IFC files also contain other data like property sets and their values and are therefore comparatively large. The extracted geometry in GLB format, together with all metadata required to visualize the 3D building model, is already significantly smaller. Applying Draco compression results in geometry that can be several orders of magnitude smaller than the original IFC file.*

Pre-processing the geometry also enables optimizations for more efficient rendering of the 3D model in the front-end application. For example, geometry of related elements can be merged into a smaller number of larger geometry batches, to reduce the number of draw calls required to render the 3D model. Different merging strategies are possible, for example by material, or by spatial relationships.

At this stage, it is also possible to combine several IFC models into one project for visualization. In practice, it is often the case that the complete information is not contained in a single IFC file, but each trade has their own specialist IFC model that is coordinated with the others. For example, in addition to the architectural model, there are commonly separate models for landscaping, HVAC, and electrical installations. To support this use case, multiple IFC files that share a common spatial building structure, i.e. where the definitions of buildings and building stories match, can be imported together into a single project on the buildingTwin platform. Elements from all IFC models are linked together according to their spatial relationship, so that, e.g. electrical installations from one building story are linked to the corresponding building story from the architectural model. In the end, all elements are combined into a single optimized geometrical representation.

Other data contained in the IFC file, like property set definitions and values, are stored in a database on the server and are only transferred on-demand, e.g. when the user selects some elements in the front-end. This way, only the minimal amount of data is transferred between front- and back-end.

To provide all building data to the front-end application and to other client applications, the back-end offers an HTTP API that allows to query and update all project resources like property set definitions, property values assigned to elements, documents linked to elements, or real-time measurements. This HTTP API is primarily used by the front-end to access and update all project resources, but it can also be used by other tools, for example to automatically import data or to automate workflows.

All API requests require authentication, which is used to limit requests to resources that a particular user has permission to access. To facilitate this, the back-end implements a fine grained permission system to grant or deny operations like creating, reading, updating, or deleting certain resources. The resources can be project level resources, like individual elements, or element level resources, like documents that are attached to particular elements. This enables flexible workflows like, for example, to share only a particular type of element, e.g. all windows, with the relevant construction company and to allow them to enter properties and to upload data sheets for these elements.

Similarly, real-time timeseries data can also be sent to the buildingTwin platform via an HTTP API, or alternatively via MQTT. These protocols are supported by most Internet of Things (IoT) devices or gateways, and there are many existing timeseries databases or IoT platforms like ThingsBoard [15] available to collect and store the data. Sensor measurements can also be acquired from existing building management systems. In this case, a gateway is used to collect the BMS data via BACnet, Modbus or other protocols, and to forward the data via HTTP or MQTT to the buildingTwin back-end. The flexible interfaces also enable other tools like simulations or forecasts to provide timeseries data for a building. One common example is weather data, that can be queried from a weather service and added as timeseries data to a building.

3.2 Front-End

In conversations with BIM practitioners from different industries, we found that one of the most commonly shared requests was to provide an intuitive, user-friendly interface to BIM and building operations data. Because, often, the target users of such a platform are not BIM users themselves but building managers or craftsmen. Therefore, we focused on making the platform and the data easily accessible. For that reason, we also avoided using any technical BIM terms like IFC class names. Instead, we translated IFC classes to everyday terms. For example, we use “room” instead of “IfcSpace” to describe the type of a spatial volume associated with a building story.

The web-based front-end application therefore focusses on providing a clean, understandable graphical user interface to visualize and interact with the building data. Providing a web-based user interface enables users of the buildingTwin platform to access building data from any device with a modern web browser, like smartphones, tablets, or desktop computers, without having to install special software on their device.

After logging in, the user is presented with an overview of available projects, filtered based on the users’ permissions. For individual projects, the user interface is centered around an interactive 3D visualization of the building model rendered using WebGL. Users can easily navigate the building model, e.g. show individual building stories, or focus on specific spaces, using a hierarchical listing of the spatial building structure. In addition, the user interface provides detailed views for additional functionality and data.

Using the interactive 3D building model any visible element can also easily be selected by clicking or touching it in the 3D visualization. Alternatively, a complete list of all elements can be accessed through the user interface. This list can be quickly filtered by entering keywords to search through element attributes like name, type, material, or ID. Selecting an element also provides an additional view with all element attributes, assigned property sets, and their specific property values. The properties for selected elements are loaded on-demand from the back-end. All loaded property values can then be updated in a spreadsheet-like user interface and saved back to the database.

The element attributes view also allows to upload documents like data sheets or photos to the buildingTwin platform and link them with the element. All stored documents can be listed for each element, and many common file types, like PDF, images, or videos, can be directly viewed inside the buildingTwin platform, without any extra software or download step.

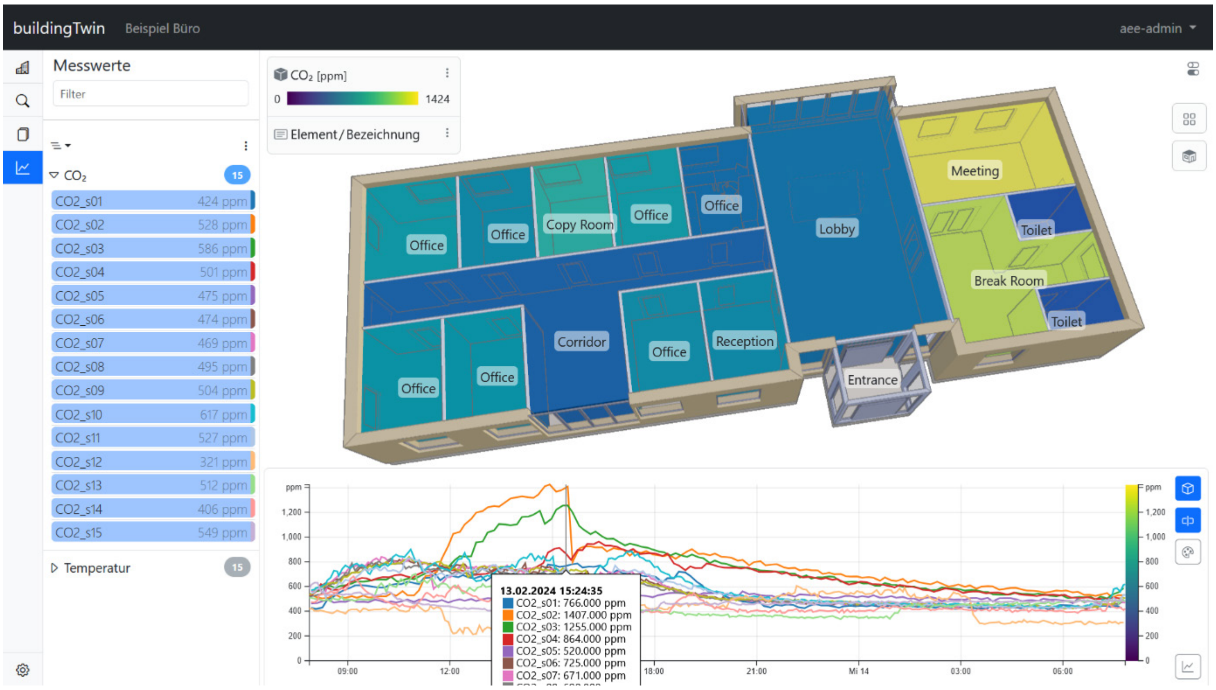

Figure 3. *Screenshot of the buildingTwin web application visualizing real time sensor measurements on the 3D BIM model of a small office building. Labels in the 3D model indicate the name of each room, taken from BIM properties of the model.*

To provide better insights into BIM data and enable spatial analysis, property values assigned to individual elements can also be visualized and compared in the 3D building model. Numerical or Boolean values can be visualized by coloring the geometry of the respective element in the 3D model according to a color scale. Upper and lower bounds of the color scale, as well as the color scheme, can be easily adjusted for different use cases. All property values can additionally be added as labels to the 3D model. The labels are automatically linked to the position of the corresponding element in the 3D model. This is especially useful to display names or descriptions in the 3D model, so that users can quickly identify elements or spaces. An example of this use case is shown in Figure 3 where room names taken from BIM properties are shown in the 3D representation.

In addition to the visualization of static property values, the buildingTwin platform also provides visualization of real-time measurement data. Measurements can be visualized in traditional 2D timeseries charts, but they can also be linked to one or more elements in the BIM model. When a measurement source is linked to an element of the BIM model, the 3D geometry of the respective element can be colored according to a color scale, similar to how numerical BIM properties can be visualized. Figure 3 shows how the measured CO_2 concentration in rooms can be visualized in real-time in the 3D model by assigning the measurements to spaces in the BIM model. Together with the room name labels, users can get a good understanding of the current state of the building and can quickly identify areas of interest.

4. Use Cases

The integration of all relevant data about a building, from planning BIM data to real-time sensor measurements, into a single platform facilitates many different use cases. Two main use cases are the documentation of the “as-built” state, by managing element properties and documents, and building monitoring, through the integration of real-time measurements. The real-time measurements can also be used to send automatic alerts to users, for example if some measurement is outside of a user defined range of acceptable values. But having all data available also enables the platform to be used as the basis for additional smart services like energy efficient building automation, where real-time data and attributes are used to control equipment and devices in the building. Possible use cases for the platform therefore include, for example:

- “As-built” documentation
- Energy monitoring and benchmarking
- Occupancy and space utilization
- Indoor air quality and comfort monitoring
- Alerting system
- Energy-efficient and comfort-enhancing building control

While features for data management and real-time monitoring are built into the buildingTwin platform, other use cases can be implemented by connecting to the platform via its HTTP API from other tools and use the aggregated data e.g. to run building simulations, to compute forecasts, or to derive optimized control strategies for operating the building or certain devices in an efficient manner.

4.1 Office Building Ventilation System

As a demonstration for extending the buildingTwin platform for such use cases, we implemented an automatic control strategy for a ventilation system in an office building based on aggregated data on the platform. The goal was to optimize the ventilation system to improve air quality, improve user comfort, and reduce cooling demand during summer.

Because the office building did not have an existing building management system, and there were no sensors available, the building was retrofitted with LoRaWAN [16] sensors that measure temperature and CO_2 concentration, as well as other information in each room. Additionally, a sensor to measure outdoor temperature was added as well. All LoRaWAN sensors communicate with a single gateway, that forwards the data to the buildingTwin platform via HTTPS. Using the combined data from these sensors, a strategy to control the ventilation system was implemented, based on two targets:

- Improved air quality
- Night-time ventilation during summer

A schematic overview of the involved components and services is visualized in Figure 4.

To improve air quality in the offices, the ventilation system is automatically activated if CO_2 concentration rises above a certain threshold, e.g., above 900 ppm. Once the CO_2 concentration falls back to normal levels, below 500ppm, the ventilation is automatically stopped again.

Similarly, another goal was to cool the building during hot periods in summer by implementing night ventilation. After normal office hours, the ventilation is automatically activated once the outside air temperature is below indoor temperature. It stops again if a user defined target temperature is reached, the outside air temperature is warmer than indoor temperature, or office hours start again. This minimizes the impact for the office users and reduces cooling demand during the day.

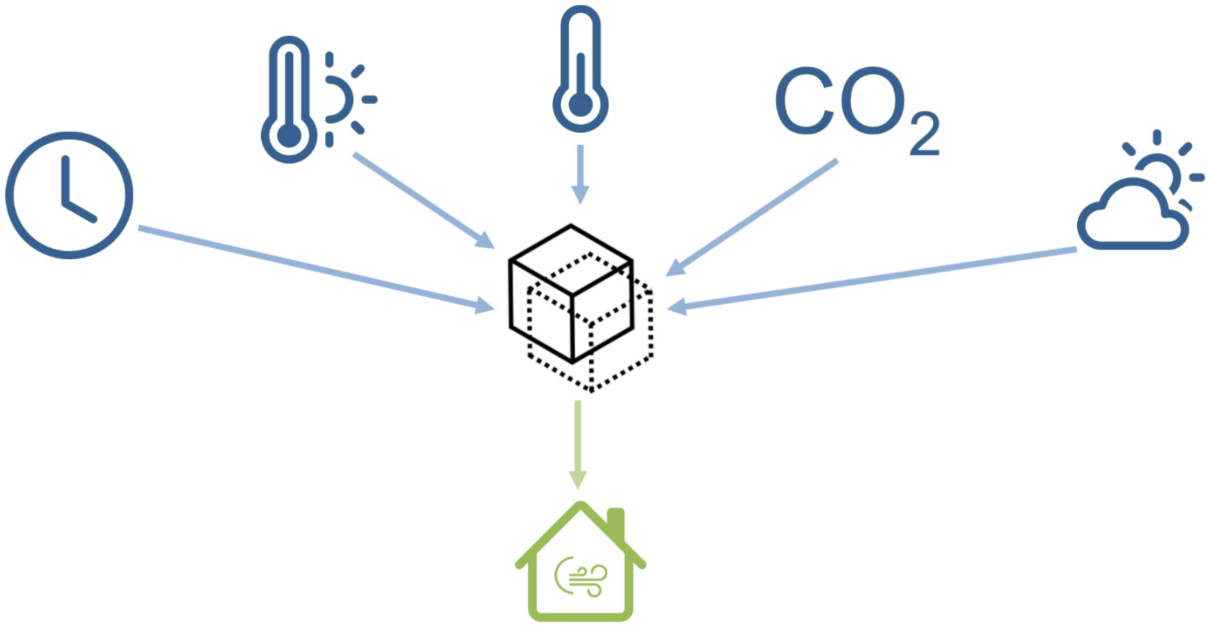

Figure 4. *Schematic overview of an optimized ventilation control strategy. Measurements from different sources (top, blue), like sensors or weather services, are aggregated on the buildingTwin platform (center), where they are used to efficiently control the ventilation system of a building (bottom, green).*

The limits and target values of this control strategy can be defined as BIM properties in the building model and can therefore be easily changed from within the buildingTwin web interface by any authorized user. Similarly, the current real-time state of the ventilation system is in turn fed back into the buildingTwin platform, where it can also be visualized and analyzed.

We found that the control strategy works as desired by the office users. Especially during meetings with many people, the air quality was significantly improved using the CO_2 based ventilation control. At the same time, the ventilation system is only activated as long as necessary. During our evaluation, we also compared the installed outdoor temperature sensor to publicly available temperatures from a weather service and found that they matched well.

Therefore, for this simple use case, the outdoor sensor could also be replaced with public weather data, which can be easily integrated into the buildingTwin platform, saving on additional hardware.

A similar control strategy, based on just sensor measurements, can also be implemented using existing building management systems. But the buildingTwin platform offers the flexibility to also integrate other data, for example from BIM attributes, from weather services, or from simulation results, into the process. And using the web-based user interface, the data is easily accessible for all authorized users. For example, future extensions to this control strategy could also include forecasts of heating or cooling demand, based on historical measurements and current weather forecasts, and optimize control of heating and cooling systems based on these predictions to reduce overall energy consumption.

5. Conclusion

We demonstrated the web-based buildingTwin platform to collect, manage, and visualize all information about a building in an accessible way. The initial data is based on the BIM model from the planning phase, independent of the actual planning software used. The BIM model is optimized for use in a web-based environment. Anyone can access and contribute to the building data using a web browser, no special software is required. The user interface is kept as simple as possible to be intuitive for a wide range of different users. This enables executing companies to contribute their data directly to the BIM model. In addition to the data from the BIM model, many additional (real-time) data sources can be linked and visualized to provide a comprehensive view on the current state of a building throughout its lifecycle. This can be used to optimize building operation and provides the foundation to develop advanced predictions and forecasting models to further improve building efficiency.

Data availability statement

This work is not based on any particular data. The IFC projects used during the development and testing of the platform were provided by industry partners and cannot be shared. However, the concepts described apply to any IFC project.

Underlying and related material

There is no other related material available.

Author contributions

Andreas Riffnaller-Schiefer: Investigation, Software, Visualization, Writing – original draft

Tobias Weiß: Conceptualization, Funding acquisition, Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

Funding

This research was funded by the Collective Research program of the Austrian Research Promotion Agency (FFG).

Acknowledgement

We would like to thank our industry partners BIG, E-Steiermark, LIG, Nussmüller Architekten, pde Integrale Planung, and PORR for their contributions and support of this project, and ÖBV for coordinating our work with the industry partners.

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