2023 European Conference on Computing in Construction
40th International CIB W78 Conference
Heraklion, Crete, Greece
July 10-12, 2023

DIGITAL TWIN SYSTEMS FRAMEWORK FOR BUILDING FAÇADE ELEMENTS TESTING

Calin Boje[1], Nico Mack[1], Sylvain Kubicki[1], Ana López Vidal[2], Carlos Casado Sánchez[2]
Pascale Brassier[3] and Antoine Dugue[3]
[1]Luxembourg Institute of Science and Technology, Esch/Alzette, Luxembourg
[2]Cartif, Valladolid, Spain
[3]NOBATEK/INEF4, Anglet, France

Abstract

This research is part of the MetabuildingsLabs project on Open Innovation Test Beds, aimed at providing a platform for open source, open access and open data for technology providers, with a focus on building facades. Within this paper, we adapt the digital twin paradigm for a façade testing facility, using open tools. We formulate a conceptual system architecture based on previous research, with the key particularities of testing beds and the system end-users. We describe key software and IoT components and the role of semantic models. The approach is demonstrated on a scaled-down 3D-printed model of the planned building.

Introduction

The testing and validation of novel façade components play an important role in increasing the energy performance of our buildings. Novel manufacturing capacities such as 3D printing or predictive control enable innovative adaptive façade elements for which the testing and validation are of greater importance to help industrials in the design process to characterize the performance of new components, and to speed up the innovation process. This process requires specialized facilities with controlled testing conditions. Each test undergoes specific procedures, which requires adaptive infrastructure and continuous onsite monitoring to characterize the behavior of tested façade elements in various scenarios. The current way of testing is handled manually by test bed operators, and the tools used are highly fragmented in monitoring, transferring, and processing collected data. The motivation of our work during the METABUILDINGLABS[1] project is to streamline and digitalize the process for façade element testing beds, thereby improving its efficiency. For this purpose, a series of building envelope testbeds are being designed and built. These are 1:1 scale, real conditions, standardized physical testing facilities, called Open Source/Open Access/Open Data Building Envelope Testbench, termed O3BET. Their purpose is to accelerate innovation for small and medium enterprises.

Within the built environment domain, Building Information Modelling (BIM) tools play a key role at design and construction stages, while a Digital Twin (DT) approach can complement this with increased monitoring, fault detection and actuation when it comes to testing facilities. There are many existing tools for BIM modelling and management which could be used for O3BETs. Whilst the same is true for DT, the challenge addressed in this paper starts with identifying the scope of the O3BET-DT services and narrowing down the necessary key components for enabling a DT paradigm. Additionally, the openness of these tools also needs to be considered, to make this accessible and replicable across several EU countries contexts.

Within this paper we propose a conceptual framework of the O3BET-DT, derived from existing research, and discuss its particularities, aimed at helping operators in the daily management, and a more efficient testing process for the characterization of the façade components.

The paper is structured as follows. Background on testing beds, the use of BIM and DT is provided in section 2. An adapted O3BET-DT framework is outlined in section 3. A survey of available tools, technologies and data models which fit into the framework are described in section 4. Section 5 demonstrates a miniature 3D-printed testing bed integrated into an already existing system and describes implementation challenges encountered.

Background

O3BET

The current work is part of the METABUILDINGLABS EU horizon 2020 project, which aims to deliver so-called Open Innovation Test Beds (OITB) for easier testing of façade components across EU country networks of technology providers and testing facilities. Within this project, O3BET facilities try to implement the best practices from previous test bed networks, while also adding new functionalities. The digitalization of the process is one of the aims of the project. A well-known such network is the PASLINK one created from the European PASSYS (Gicquel, 1988) project (Passive Solar Components and Systems Testing) having started in 1985, focused on the use of test cell facility as a way to evaluate the performance of passive solar building components in real conditions and provide more information on building design and simulation tools (García-Gáfaro et al., 2020; Martínez et al., 2019). A key limitation of past

[1] https://metabuilding-labs.eu/

developments is the significant effort required to manage the tests, which can be improved through digitalization.

Within this paper we focus on a singular aspect, the implementation of the DT paradigm for a building testing facility, also known as O3BET-DT in this case. In practice, an O3BET consists in a relatively small-scale building, with dedicated spaces also called cells which are designed to test individual types of façade components (see Figures 2, 4 and 6). Thus, each cell can be used to test a component at a given time, under different conditions. This means that not only is the building being monitored as a whole, but each cell is monitored and controlled individually, as well as each façade component. This creates a relatively complex monitoring facility in terms of its spatial structure and delimitations, which requires careful management to ensure good tests practice and lead to convenient and reliable product validation for technology providers. An additional role of the O3BET is the standardization of the testing procedures, aiming for comparative studies and benchmarking of façade performance.

The current working procedure for tested elements is led by O3BET operators who engage with the technology provider as a client through a contract which specifies the types of tests and their configurations, the monitoring required, its length, the number of testing cells, etc. This means that an O3BET might operate with different clients at the same time and is required to operate effectively during and between testing campaigns. The current working procedures are supported by the latest technological infrastructure (sensing equipment, etc.) but the data collection and analysis process are fragmented, this requiring many transformations from gathering to analysis tools. Additionally, the real-time monitoring system in place has limited interactions with its end-users, expected to send malfunction messages to operators and managers, but not accessible to technology providers. This causes a time-consuming process, which we plan to improve by delivering a DT system which brings cohesion to the data and integration of the monitoring and control processes involved on the ground.

The role of BIM

The BIM plays a key role in representing the building design domain from early stages to construction. In post-construction stages BIM remains an important provider of structured information to many tertiary fields for building operation, maintenance and is seen as a key component of the building digital twin.

The O3BET relies on a BIM model for its 3D representation, but most importantly to exchange information on the tested building components from testing phase to their adoption by the market, which will rely on BIM objects to design and simulate the energy performance of novel façade elements. We can consider the O3BET building design to be "fixed" or static, but the envelope components regularly change with each testing campaign. We expect that O3BET operators and technology providers will need to model façade elements using different BIM tools and exchange this information across a well-defined workflow. Although BIM is implemented across multiple construction domains, and in numerous BIM-compatible platforms, the Industry Foundation Classes (IFC) schema model is the format which describes the interoperability of BIM models. Being an open schema model covering structural, mechanical and electrical domain concepts, it acts as a good reference for the O3BET model representation. Concepts such as associations and hierarchies also allow the delimitation between building and façade elements, facilitating modular management of the O3BET.

To ensure a structured and clear transfer of test information, an additional layer of standardization can be applied on top of the IFC schema models using the eCOB standard. eCOB is a Spanish development which stands for "Creation of BIM Objects Standard", developed by the Institute of Construction Technology of Catalonia. Its rigorous development and open documentation are useful in defining BIM objects in line with the latest official release of the IFC schema, IFC4 Add2 TC1. This allows exact specification of façade element properties required for calculations, tests and the resulting material passport. Additionally, alignment with the recent BIM standards on data templates, ISO 23387:2020 should be considered, as this specifies how construction object data templates should be considered across their entire life cycle (Mêda et al., 2021).

The role of DT

Digital twins are applied in numerous fields and with several contexts. Within the built environment, the most common use of a DT is at the operation stage where physical assets are monitored, controlled and acted upon, such as: indoor air quality, energy consumption, solar energy gains.

Recent research on the topic of DT has experienced a resurgence, with studies such as with (Negri et al., 2017),(Tao & Zhang, 2017), (Gharaei et al., 2020) and (Moyne et al., 2020) having compiled lists on its many definitions, importance, incorporated technologies, and various requirements.

For the O3BET context, the DT fulfills a key role in providing monitoring and control mechanisms, which are beyond the scope of the BIM model or the separate sensing networks in place. We consider the BIM as a key component of the O3BET, representing the building domain information, and acting as a source of static data for DT services on top. The DT deals primarily with dynamic data gathering, streaming data from sensors for continuous monitoring and analysis, and actuation when necessary. Most of all, the DT paradigm would facilitate cohesion of the integrated components as a singular system, and provide real-time monitoring of tests.

The literature refers to several existing examples of DT for buildings (Chevallier et al., 2020) (Qiuchen Lu et al., 2019), for supply chains (Barykin et al., 2020) and on construction sites (Boje et al., 2020), (Sacks et al., 2020). DT for factories have been defined and applied by (Tao & Zhang, 2017), but only a few studies consider testing beds for building elements, such as (Molinari & Rolando, 2020) with a simplified framework on simulation and calibration of a thermal model. More recently, (Merino et al., 2022), propose a technical pipeline for implementing DT on buildings.

Looking at specific DT implementation requirements, (Gharaei et al., 2020), (Moyne et al., 2020), and (Shao & Helu, 2020) provide several perspectives on requirements ranging from functional to non-functional ones. Functional requirements were aggregated and generalized for the built environment domain in the work by (Boje et al. 2022). We can consider these in tandem with so-called abilities of DT, proposed by (Boje et al., 2020), where we see BIM play a quintessential role as a data provider. Adopting the above-mentioned requirements for the O3BET use case, we propose a conceptual framework for testing bed DT, which we describe in the next sections.

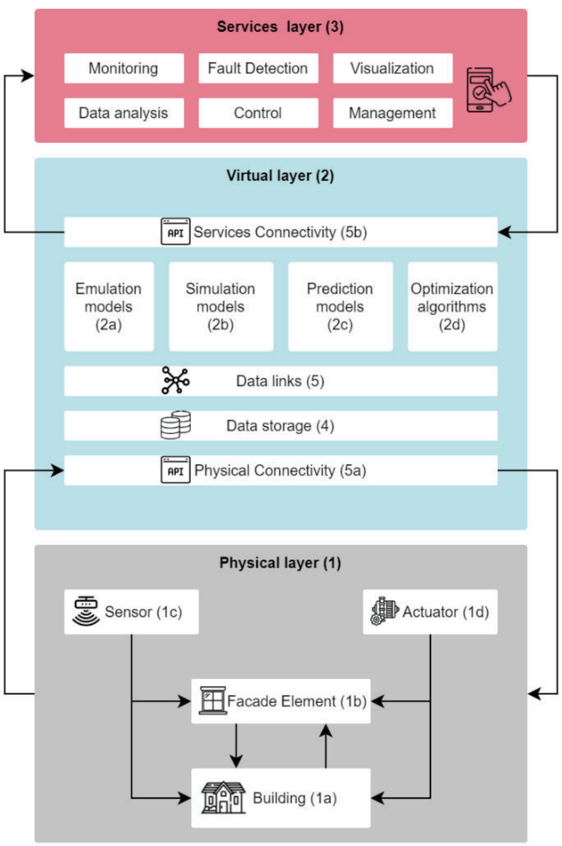

Figure 1. the O3BET digital twin conceptual architecture

Methodology

The research methodology within this article is concerned with adapting the O3BET process to a DT approach. This is also supported by previous project work on identifying digitalization needs of the O3BET, but which is only briefly addressed here. Throughout this article we introduce several specific technical needs of an O3BET, and emulate these on existing DT implementation frameworks, which were reviewed and discussed. Our adapted framework is then validated on a demonstrator system which outlines limitations and future challenges.

O3BET Digital Twin

Conceptual system architecture

Following the 5-component model for DT, proposed by (Tao & Zhang, 2017) and generalized for the built environment in (Boje et al., 2022), Figure 1 presents an adapted framework for the O3BET use case. Although conceptual, it describes several important components, which guide us towards a technical implementation. The framework considers 3 conceptual layers: (1) the physical layer – representing the real-world assets, (2) the virtual layer – containing models and algorithms, (3) the services layer – use-case specialized software components (e.g. visualization service, fault detection service, etc.). Across these layers we also include the data storage component (4), which lies inside the virtual layer, as well as the data links (5) which need to provide adequate mapping of virtual and physical assets. For simplicity, within this framework we describe a low-bound API which connects the physical layer with the virtual models (5a), and a high-bound API which allows services to interact with the virtual layer. Within the virtual layer, these can be coupled using data graphs for convenience. Overall, the proposed conceptual architecture is in line with the DT paradigm proposed by (Grieves, 2014).

Superimposing our O3BET requirements on this architecture, we define: (1a) the O3BET building, (1b) the façade component for testing, (1c) the sensor and (1d) the actuator as the physical layer component types of interest. Technically these elements are integrated by the sensing infrastructure and interoperable communication network in place, which are described further in the next sections.

The virtual layer of the O3BET comprises the virtual data models for various purposes: (2a) emulation – for data modelling of semantic concepts involved, (2b) simulation – for the integration of simulation tools for use cases such as thermal and energy, (2c) prediction – for the integration of prediction models and (2d) optimization – for the integration of algorithms and optimization models. The data storage components are varied and thus need to account for hybrid datasets. We propose SQL table databases for larger structured data sets, a graph database (hosted on a triple store) for connecting the virtual layer models, and other noSQL databases for everything else.

The lower-end API deals with physical twin data connectivity, by which sensor and actuator data is integrated in the upper layers. The high-end API exposes several functionalities to use the model layer and support services. The digital services layer (3) for O3BET comprises of basic functionalities such as:

1) **monitoring** – for a seamless stream of data used for other services, such as 2) and 3) below

2) **data analysis** – for cleaning, pre-processing and automatically analyzing sensor data from tests,
3) **fault detection** – for fault management during active testing campaigns,
4) **control** – for actuation and sensor configuration,
5) **management** – allowing certain users to configure the DT when required and
6) **visualization** – web-interfaces for convenient end-user interactions with the models and data at the presentation layer. 3D BIM geometry and semantics, incoming sensor data and fault detection data should all be available for visualization for end-users.

The proposed architecture is generic enough to allow several types of tools and technologies to be implemented for any DT system. Within this article, the challenge lies in defining the semantic data model which underpins the system – the data links and the necessary models for the O3BET use case.

Virtual models

The specified "emulation" models (2a) refer to data schemas which represent real-world "things" in the virtual world. Technically we can refer here to data models within code applications, but these need to follow certain data exchange requirements with other applications from the nearby domains. For the O3BET case, the building, its façade components and sensing infrastructure need to be emulated.

As discussed previously (section 2), we consider the IFC schema as the building representation model. Considering the schema version 4.2[2] in particular, we can identify several important types of components which would be stand-alone (singular) types for façade elements: IfcWall, IfcCurtainWall, IfcRoof, IfcWindow, and IfcShadingDevice. These are important to define together with specific sets of properties, to deliver testing outcomes into BIM object formats. We used the eCOB guidelines to define several templates, corresponding to different IFC building element types. These guidelines structure information based on Property Groups or "Psets" (abbreviation of "Property sets") recognized by the IFC schema, which is complemented by other property groups proposed by eCOB. Each group of properties has determined value types and ranges where applicable, whether it is a prescriptive value based on technical regulations or a value declared by the manufacturer. With the BIM objects resulting from O3BET testing, its corresponding property sets are used to define post-test values and provide added value to manufacturers and designers down the supply chain.

The building sensing equipment can be described by things such as IfcSensor, IfcActuator and the subclasses of the IfcDistributionElement type. For technical implementation using the IFC schema, there are several open-source options, most notably the IfcOpenShell3 and xbim toolkit4 libraries which work on multiple IFC schema versions. These allow convenient IFC file parsing and editing, or 3D visualization, allowing coupling of BIM model information with other domain specific applications. Thus, the O3BET can be fully represented using the IFC schema, but the BIM model alone is limited when it comes to monitoring applications.

To develop a DT, a network emulation model is required. Incoming sensor data, outgoing actuation controls, the handling of message events and integration with the other emulation models needs to be specified and implemented. Openly available data models such as SSN5 for representing networks of sensors which also includes SOSA (Sensor, Observation, Sample, and Actuator) for representing observation events, are suitable candidates. Alternatively, the SAREF6 models are similar in function for representing smart appliances at a higher level, keeping track of the hardware infrastructure on the O3BET, which under SAREF are classed as devices associated with other useful concepts, such as "commands" – for acting upon a state in actuation, "properties" and "measurements". The described open data models are designed as semantic web ontologies, under the Resource Description Framework (RDF) and Web Ontology Language (OWL) schemas.

The remaining emulation models are more O3BET specific, required for context creation. Models which allow planning of testing and monitoring campaigns, keeping track of schedules, simulations and optimization results, raised events, etc. Additionally, for the correct monitoring of a testing campaign we specify the need for a rules engine to help identify anomalies and raise alerts. Given this context is application specific, we recommend using internal models and aligning them semantically to the previously mentioned models (IFC, SSN/SOSA, SAREF, etc.). This would be a key model for data integration and contextualization of testing campaigns. We recommend following implementations such as the open source building data management platform BEMServer7, which falls under this domain. Alternatively, the Brick8 schema is also used in various implementations, most notably by (Merino et al., 2022), in combination with IFC models.

[2] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/

[3] http://ifcopenshell.org/

[4] https://docs.xbim.net/

[5] https://www.w3.org/TR/vocab-ssn/

[6] https://ontology.tno.nl/saref/

[7] https://www.bemserver.org/

[8] https://brickschema.org/

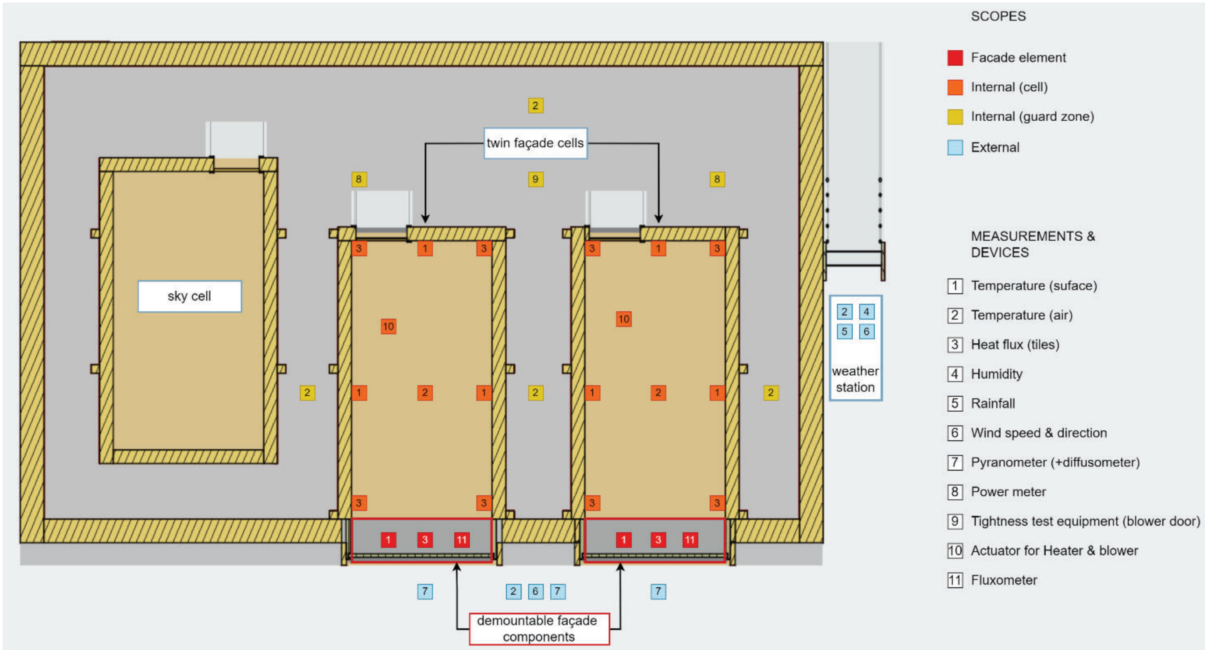

Figure 2. O3BET sensor configuration and placement for thermal characterization testing

Sensors, actuators and physical equipment

Most of the sensors in the O3BET are fixed sensors distributed inside and outside the cells. Additional temporary sensors will be installed in the tested façades, with types of sensors depending on each test. As a starting point, a sensor configuration for the thermal characterization test has been considered. Regardless of whether the sensors are fixed or temporary, the sensors are classified in relation to heat transfer calculation (1) and to the analysis of climatic conditions (2). The first group integrates surface and air temperature sensors and heat flux sensor placed on the cell walls and on the tested enclosure or façades. A weather station with temperature, wind speed and direction, humidity, rain sensors and pyranometers to quantify solar radiation will be installed to monitor the external weather conditions throughout testing. The planned layout of sensors around cells is shown in Figure 2. For the thermal model characterization, sensors with high sensitivity are required such as in the case of temperature sensors where PT100s are preferred over thermocouples of any type. These comply with current industry practices.

The sensors are wired to a datalogger per cell. The dataloggers provide access to the sensor data via an ethernet connection through a router and switch to which both a data backup system, the local computer and cameras are connected, as indicated in Figure 3.

Data storage and links

High-bound connectivity of the virtual models with services can be achieved via traditional web-based protocols (HTTP/S) using REST API and CRUD operations. In a typical server-client architecture we consider the services to be client applications. The open source API specification[9], (aka swagger) permits convenient development of open APIs and allow data exchange over XML and JSON serializations. Because most web applications consume JSON payloads, the loose data structure of JSON objects means that there is potential loss of semantics when passing from one application to another (e.g. from virtual models to a service app), but this can be remediated by using the newer JSON-LD format, which is compatible with linked data standards.

The low-bound API deals with connecting the physical sensing infrastructure by collecting sensor data and controlling or actuating in return. Datalogger data is transferred to the DT system using an internet connection,

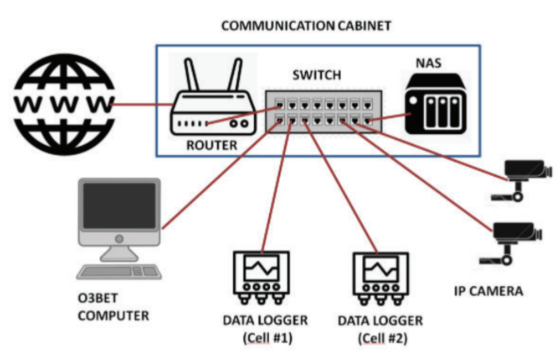

Figure 3. O3BET cells monitoring network configuration

9 https://swagger.io/specification/

whilst also storing the raw data locally on site. Additional steps are required to ensure data structures and transfer integrity with upper-bound APIs.

Fault detection and Visualisation services

We have identified several important types of services, as mentioned on Figure 1, for O3BET-DT end-users. Amongst the most impactful ones are the fault detection and visualization services. The first is important in early detection of un-anticipated errors during monitoring, facilitating timely intervention. The second is convenient visual support for continuous management of the monitoring process and exchanges with the client or technology provider.

The fault detection service needs to employ post-processes on sensed data, and a set of well-defined rules for raising appropriate alerts on data outliers or potential operation problems (loss of air tightness, abrupt loss or gain of temperature inside testing cells, sensor malfunction, etc.). In order to do so, the fault detection service needs to rely on post-processed data points in pre-determined formats, and pass these values through a rules engine. Technically, this can be implemented within the aforementioned BEMServer, with the addition of an open-source rules engine (embedded or external servers), such as RulesEngine10 from Microsoft, or OpenL Tablets11, or similar business rules engines. If needed to align with semantic web tools, most triple stores include basic Description Logic Rules.

The visualization service is primarily used to visualize the 3D BIM geometry, but can be used to identify each testing cell, its corresponding façade element under tests (see Figure 6), as well as the exact positions of devices. The visualization service can quickly render monitored data and highlight any concerns, working well in tandem with outputs from the fault detection service. For technical implementation of 3D viewing, there are many options for open source web development, such as Ifc.js12, or xbim toolkit wexbim for example.

Simulation, prediction and optimization

One of the prime requirements for façade element testing is the ability to simulate a calibrated model, whereby parallel predictions and optimizations can be carried out to deliver a façade component characterization model. Thermal energy simulations for façade elements are the most valued, which need to be calibrated with incoming sensed data for increased accuracy. There are several open-source libraries, such as OpenModelica[13] or Octave[14] where the specific model scripts can be created individually and plugged into an application. This makes it convenient to include new simulation capabilities quickly, and update existing ones.

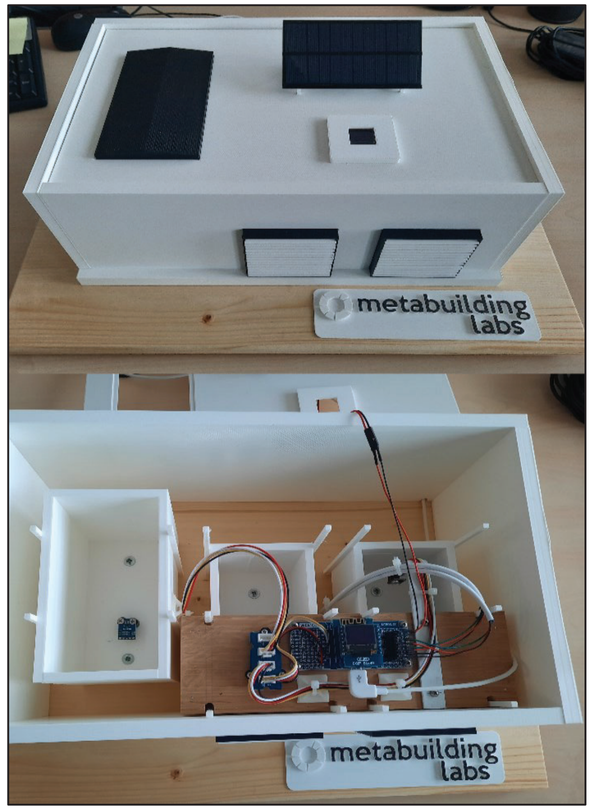

Figure 4. 3D-printed O3BET and physical sensing equipment

O3BET demonstrator

The physical

The O3BET demonstrator is a 1:40 scale 3D-printed replica of an actual O3BET (Figure 4). The overall idea of the demonstrator consists in acting as a drop-in replacement in case an actual O3BET is not available. The architecture of the sensor data acquisition system is depicted in the Figure 5. The *physical layer* comprises a representative range of sensors that are potentially also available in a real O3BET, e.g. temperature and humidity sensors, brightness sensors, digital (switches) and analog inputs (monitoring of solar panel power generation).
The *acquisition layer* is responsible for aggregating all the signals from the various sensors. In a real O3BET, a data acquisition system like LabView or a SCADA system would act as a sensor concentrator. In our demonstrator we used a small ESP8266 WEMOS microcontroller as a substitute for such a system. The *network layer* takes care of transmitting sets of aggregated data to the next higher layer, using either wireless and/or wired transmission

10 https://microsoft.github.io/RulesEngine/

11 https://openl-tablets.org/what-is-openl-tablets

12 https://github.com/IFCjs

13 https://www.openmodelica.org/

14 https://octave.org/

standards. The *integration layer* consolidates the various data streams originated from the network layer and forwards the data to the *persistence layer* which is responsible for storing the data. Even though we've only described the data acquisition side of things, we'd like to emphasize the fact that the data exchange can be bi-directional, thus making it possible to control *actuators* in the O3BET.

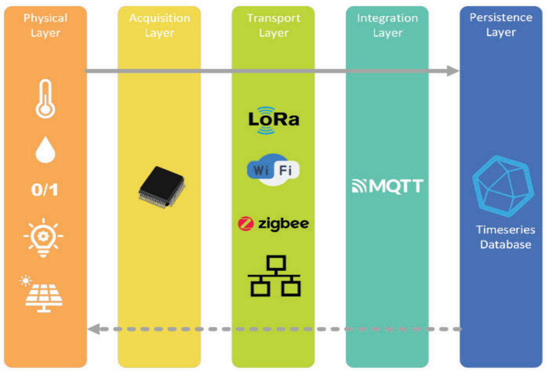

Figure 5. Sensor Data Capture System

The virtual and services

The virtual layers of the demonstrators are tested on a software system which uses its own ontology graph to map a IFC geometry, tasks and sensing concepts. These were mapped to the IFC and SSN ontology schemas, although not all concepts are in use. This allowed quick testing of the O3BET demonstrator using its BIM model and interacting visually with it, as well as streaming time series data on a custom dashboard. The system contextualizes gathered data and issues visual cues on the status of physical components based on several rules (as indicated by the green and red coloring of BIM objects in Figure 6).

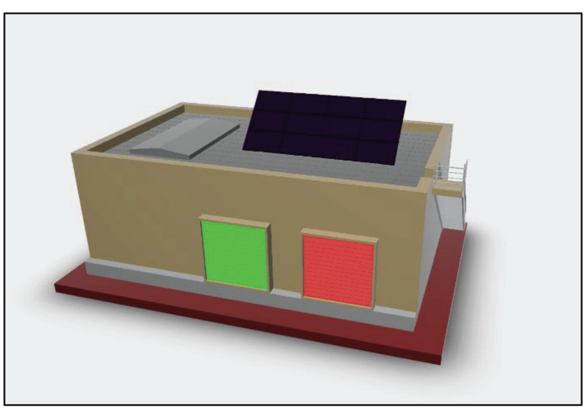
Figure 6. O3BET BIM model with fault detection visualization

So far, we have tested the integration approach, visualization and fault detection, with others planned for future work. Although the current interactions with the BIM and sensor data render in near real-time, we expect that post-processing data and simulations would have to be run in parallel and independently. Alternatively, an appropriate sampling rate needs to be chosen in updating the latest information. For O3BET testing, the real-time monitoring is only important for timely fault detection. However, this is more useful when actuation is allowed, as opposed to waiting on human intervention.

Demonstrator Limitations

The 3D-printed replica brings several simplifications which cannot be tested in practice. Firstly, its small size and lack of adequate insulation means that sensor data cannot be considered as it would be on the real scale. The demonstrator was developed solely for testing the data pipeline. Secondly, the demonstrator has no local buffering on the incoming data so a loss of internet connection can lead to data loss. Thus, the gathered data for the real-size O3BET is designed to be stored locally and ultimately sent to a cloud-based DT-system.

Discussion and conclusion

Within this article we proposed a conceptual framework for the O3BET-DT, which encompasses the use of BIM and sensor networks to facilitate the streamlining of building façade components testing. The challenges on O3BET particularly rely on adapting existing information models to aid the management of the building, its cells and tested façade elements. This can be partly met by BIM models, particularly the IFC schema for the building representation. The monitoring and actuation of the physical layer requires additional context definition by combining existing sensor network schemas, which also have to be aligned with technical specifications of the physical equipment. The data pipelines are simplified on the conceptual architecture, but its technical implementation presents several roadblocks. The definition of the data structure from the low-end API, its storage, interpretation is a first step to reach system data cohesion by emulating the sensors, actuators and building components. These representations were analysed by proposing several existing information modelling schemas. The use for the high-end API and services requires further post-processing, which can provide a near real-time visualization and fault detection to O3BET end-users.

Another challenge presented by the METABUILDINGLABS is providing an open suite of components for the O3BET-DT. The overall process and potential open-source tools which meet the DT requirements were indicated. We used a 3D-printed physical model which we linked across a data-pipeline to a digital platform to simulate the monitoring ability of a digital twin for demonstration purposes. Future work will be focused on replicating this approach to the planned real scale O3BET facilities as part of the ongoing research project.

Aknowledgements

This paper is published as part of the METABUILDINGLABS project, which received funding from the European Union's Horizon 2020 research and innovation program under grant agreement N°953193. The sole responsibility for the content of this document lies entirely with the authors' views. The European Commission is not responsible for any use that may be made of the information it contains.

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