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A data framework enabling BEM and BMS interoperability based on semantic web technologies and Brick ontology

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Abstract

Heterogeneous data sources are generated during the building life cycle. These data sources contain the information required for commissioning. However, their differences in data semantics, structure, and syntax make them disparate data silos, which hinders data interoperability. In this work, a framework for data interoperability is proposed as a first step toward a service-oriented digital twin enable commissioning including gap verification between the expected and actual energy performance of a building. Based on semantic web technologies and Brick ontology, this framework allows data interoperability of heterogeneous data sources, particularly Building Energy Modeling (BEM) and Building Management Systems (BMS).

Keywords: BEM, BMS, Interoperability, Semantic web technologies, Ontology, Brick.

Highlights

A viable data framework for BEM and BMS interoperability based on ontology and semantic web technologies. Moreover, the framework is developed using open-source tools.

Introduction

Proper building commissioning is one of the most effective ways to ensure that building systems and facilities perform as designed during their life cycle when they are put into service (Wu and Issa, 2012). In addition to a short payback period, commissioning can help identify and isolate failures in building operations, reduce building energy consumption and greenhouse gas emissions, and improve thermal comfort (Djuric and Novakovic, 2009; Mills, 2011). According to ASHRAE¹, commissioning is a quality-focused process for enhancing the delivery of a project by achieving, validating, and documenting the performance of facility elements in meeting the owner's objectives and criteria. One of the biggest challenges in accomplishing this task is the heterogeneity of the vast amounts of data collected by

various systems in the building industry, which necessitates extensive human labor.

The adoption of a digital twin is gaining more and more interest in the building industry (Opoku et al., 2022). More specifically, digital twin enables the creation of a high-precision virtual replica of a building's physical systems (Clausen et al., 2021; Nytsch-Geusen et al., 2019) and can help reduce costs and improve efficiency during the entire building life cycle. It enables accurate simulations, real-time analysis, building performance predictions, informed decision-making, cost-effective operations, energy optimization, and predictive maintenance (Hosamo et al., 2022; Khajavi et al., 2019).

To facilitate commissioning using a service-oriented digital twin, a data interoperability framework is required as the core of the digital twin to enable data exchange between heterogeneous data sources generated during the building life cycle. The first task of this work is to verify the gap between a building's expected and actual energy performance. The expected energy performance is simulated and predicted with Building Energy Modeling (BEM), and the actual energy performance is managed and measured with Building Management Systems (BMS). BEM comprises detailed building energy-related information such as Heating, Ventilation, and Air Conditioning (HVAC) systems. Nevertheless, it typically uses a proprietary data format. BMS manages building operation information such as ambient conditions, energy consumption, etc. Yet its data is usually delivered in a customized representation. Their differences in data semantics, structure, and syntax cause them to form disparate data silos, which hinders data interoperability (Fierro et al., 2020b). To improve the efficiency of the gap verification, as a service-oriented digital twin, it is required to achieve data interoperability between BEM and BMS. A viable solution to the data interoperability issue is to enable data exchange between heterogeneous sources through ontology and semantic web technologies. In recent years, ontology and semantic web technologies have attracted increasing attention in the building

¹<https://webstore.ansi.org/standards/ashrae/ashraeguideline2019-2386150>

industry. For data in a given knowledge domain, ontology provides a common vocabulary and a grammar for a semantic description of the data in a machine-understandable way (Taye, 2010). Developed based on ontology, semantic web technologies provide a foundation for describing, publishing, and linking data and allow heterogeneous data sources to be processed with queries and inference rules. These technologies are specified as W3C standards including the Resource description framework (RDF), the Web Ontology Language (OWL), the SPARQL query language, the Semantic Web Rule Language (SWRL), etc... This work intends to propose a viable data interoperability framework based on ontology and semantic web technologies that would enable data interoperability between heterogeneous data sources, especially BEM and BMS. This framework would be the core of the authors' future service-oriented digital twin.

This paper first reviews related work on data interoperability between BEM and BMS. Then, a framework for data interoperability is proposed and implemented in a case study. To show the feasibility of the framework, the gap verification between BEM and BMS is presented in the results section. Following the discussion section, the conclusion of this paper is drawn at the end.

Related works: BEM & BMS interoperability

BEM status

BEM intends to quantify buildings' energy performance to help designers and architects better understand the environmental impact of their decisions (Malhotra et al., 2021; Mohajer and Aksammija, 2019). More specifically, BEM can be applied for building energy prediction, estimation, optimization, management, etc. The accuracy of BEM results is determined by the quality of its input data, mainly comprising the building geometry, its construction materials, internal loads, HVAC systems and components, weather data, operating strategies and schedules, and simulation-specific parameters (Katsigarakis et al., 2019).

The BEM modeling process can be facilitated based on Building Information Modeling (BIM), which is defined by the National Institute of Building Sciences (NIBS) as a digital representation of the physical and functional characteristics of a building. Thus, BIM serves as a shared knowledge resource for information about a building that provides a reliable basis for decision-making throughout the building life cycle, from design to completion. Therefore, by definition, the models of BIM should incorporate the physical characteristics of the building and allow the analysis of its performance (Elagiry et al., 2020). However, due to the time-consuming energy analysis procedures, the building energy-related information in BIM is usually not specified or set as default values. Industry Foundation Classes (IFC) is one of the most commonly used data exchange formats for

BIM. Applying an automated data transformation of IFC data into input data of BEM tools is not a straightforward but tedious task often due to inadequacies of provided IFC files (Katsigarakis et al., 2019). Normally, the IFC file should first be properly exported from BIM and then cleaned up and corrected with the IFC tools to exclude unnecessary information and solve the geometry problems.

BMS status

BMS also known as Building Automation Systems (BAS), are systems for the integrated management of all the technical functions of a building, such as systems for access control, security, fire detection, lighting, intelligent elevators, and air conditioning. A BMS supports the daily operation of the built environment or, more precisely, ensures the operation of the devices that control the facility. As a result, a BMS contains a wealth of accurate, up-to-date, and detailed data that cannot be obtained by any other means. A single information object (e.g., the current temperature of a particular room given by accessible sensors in the BMS network) is referred to as a "data point". As an example in Figure 1 shows, the original BMS metadata is often in customized representation. However, the customized representation is usually variable and irregular because different suppliers have different rules for labeling data points (Zhan et al., 2020). The lack of any structured semantic information hinders the efficient retrieval of data points for analysis purposes, as it is not possible to select and filter data according to specific criteria such as the measurement location, the type of source device, or the type of measurand.

C-N3-012-00	RC_PG-S2_34-00	Tendance Boucle 1 Temperature Ambiante
Location ID	Equipment ID	Sensor type

Figure 1: Example of a BMS data point. The embedded metadata in the tag can tell us the location, equipment information, and sensor type.

BMS & BEM interoperability

To achieve data interoperability between BEM and BMS, one common approach is direct data mapping from BMS to BEM (Jradi et al., 2018; Zhan et al., 2020). The integrated data obtained through this type of approach is typically in a proprietary format that depends on the BEM tool used (e.g., EnergyPlus). This hinders further interoperability of data and leads to dependence on tools. In addition, some important information contained in BMS cannot be enriched as new concepts in BEM, since a proprietary format usually does not allow extension of their local concepts.

Some work has been done to structure BMS data into ontologies that conform to W3C standards to facilitate its interoperability with BIM (Chamari et al., 2022; Hu et al., 2021). But rarely work has been done to investigate the data interoperability between BMS and BEM. Although some data architectures have been proposed to integrate different data sources generated during the building life

cycle (Fierro et al., 2020a; Pauwels and Fierro, 2022), they are too general and vague and lack real-world implementation.

Apart from the problems with the proprietary BEM format, a major challenge is to have an appropriate standard ontology to describe the complex building energy data contained in the BEM. In recent years, a growing number of ontologies have been developed in the building industry. Among several open-source standardization efforts, Brick² and Project Haystack³ are the two ontologies that have seen adoption and investment from academic and industrial sources (Fierro et al., 2019), and both cover the commissioning and operation phase of the building life cycle (Luo et al., 2021). While both enable the description of building energy systems, Brick is based on RDF technologies and Project Haystack is not but recent efforts enable the RDF export of its ontological relationships. Therefore, both allow being processed with the standard query language SPARQL. Haystack offers the freedom to use small units of semantic information, called tags, to represent concepts in a non-restricted way. Composing sets of tags allows flexibility in representing different concepts, but can also lead to ambiguity if there are no rules for composition (Fierro et al., 2019). As a result, another person may have a different interpretation. Brick uses classes and relations to model buildings as shown in Figure 2, but it also support tags. Unlike Haystack, Brick uses tags to find things of relevance but not what defines things. Brick allows an unambiguous one to one mapping between concept and class, which in turn may have a set of tags. Therefore, compared to Haystack, Brick offers better consistency and clarity in representing building energy-related information in BEM.

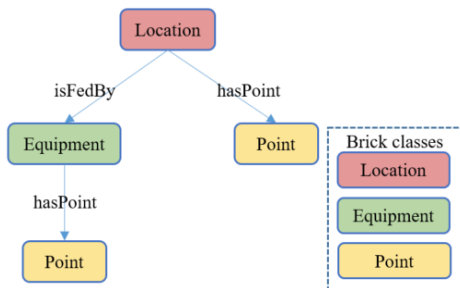


Figure 2: Brick ontology representation with Classes and Relationships.

Method proposal: a data interoperability framework

Based on previous studies, the authors propose to achieve interoperability of BEM and BMS based on Brick ontology and semantic web technologies: BEM and BMS data are first described in the Brick ontology and then unified using semantic web technologies such as OWL and SPARQL. Based on this principle, a data

interoperability framework has been developed (see Figure 4). The framework mainly consists of the following steps that aim to obtain the unified Brick model implemented on a graph database: Brick model structure guideline design, BEM to Brick, BMS to Brick, Rule-based Brick unification with a self-developed unifier, Graph data and Time series storage. To demonstrate the feasibility of the framework, the authors first present a case study building and then explain the steps of the framework based on the case study.

Case study building

Intencity⁴ is a Schneider Electric office building located in Grenoble, France. The building extends over 27.000 m² with 6 floors on the ends (blocks A and D) and 4 floors in the middle (blocks B and C) as shown in Figure 3. It is a very energy-efficient building with a consumption of 37 kWh/m²/year. The building is equipped with an intelligent BMS platform EcoStruxure⁵ which allows to collect thousands of data at a rate of 60,000 data every 2 minutes at the service of comfort and energy optimization. It also has local power generation systems that use around 4,000 m² of photovoltaic panels and two wind turbines on the roofs. The building's heating and cooling is supplied by two groundwater heat pumps that provide heating and cooling simultaneously. Ventilation of the building is provided by 8 air handling units (AHU) with energy recovery through heat exchangers.

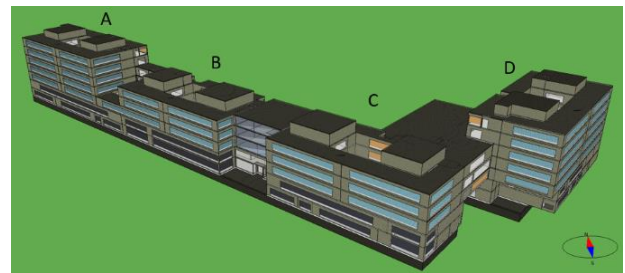


Figure 3: The case study building Intencity.

HVAC systems represent one of the major energy consumers in commercial buildings. For medium to large commercial buildings, Variable Air Volume (VAV) AHU systems are one of the most common HVAC system configurations and usually account for a large proportion of sensors and actuators in HVAC control systems (Torabi et al., 2022). In addition, they represent the majority of control points in a BMS (Gunay et al., 2022). For the study, the block C is chosen with three floors from the second to the fourth, because the ventilation of the three floors is guaranteed by the same AHU system with two coupled VAV AHUs. The indoor spaces on each floor mainly include 2 open work spaces, 1 meeting room, and 1 circulation space. The total area of the selected spaces is about 4200 m². The indoor environment of each space

²<https://brickschema.org/>

³<https://project-haystack.org/>

⁴https://www.se.com/ww/en/download/document/SEF_Intencity_flyer_EN/

⁵<https://www.se.com/ww/fr/work/campaign/innovation/platform.jsp>

is monitored with ambient temperature and CO₂ sensors. The energy consumption of each terminal unit for heating or cooling is recorded with energy meters. All terminal units, meters, and sensors are managed by the BMS in the building. The building spaces and geometries are modeled using a popular BIM tool Revit⁶, which allows IFC export. And the building energy systems are modeled using a popular BEM tool IDA-ICE⁷ with an IFC import interface. To consider the impact of adjacent buildings B and D in BEM, buffer zones are modeled to preserve internal thermal conditioning and account for inter-zone exchanges. In addition, shading masks are modeled as well to limit the effects of direct solar radiation on the zones. These masks are representative of real buildings or object bodies (e.g., the photovoltaic panels' structure on the roof). This full approach is a usual way to treat adjacent buildings not requiring full detailed simulation, and enough accurate as the temperature of these adjacent buildings are similar, for which the effect of airflow between the buildings is also considered negligible.

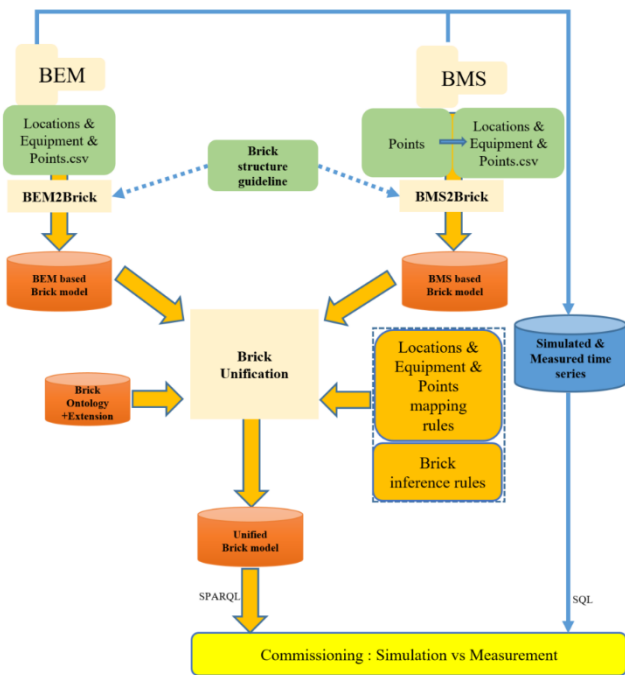


Figure 4: A data framework allowing BEM and BMS interoperability.

Brick model structure guideline design

Brick allows a building to be modeled in many different ways but there is a lack of guidance on how to structure the data model and how much detail to include (Roa et al., 2022). For example, one model may have a supply air temperature sensor associated with a zone while another model has the same sensor associated with a terminal unit in the zone. This would lead to query issues. Therefore, having an expected consistent structure in the Brick data model is critical to creating efficient and portable queries.

In this work, the task is focused on the energy consumption in each zone for heating and cooling and the zone indoor environment. Based on the focus and the practices of structuring the Brick model of BMS, a Brick model structure guideline is designed as shown in Figure 5. The sensors for monitoring the indoor environment are directly associated with the respective zone. And the energy sensors related to a terminal unit (e.g., Radiant Ceiling Panel) are associated with a main energy meter that is linked to the terminal unit. For the terminal unit, its component level is not described in the Brick model. If there are multiple terminal units of the same type serving the same zone, they are represented in the Brick model by only one equivalent terminal unit. The reason for this is that the focus of this work is on the energy consumed by all terminal units serving the same zone, and not the difference between the individual terminal units. Based on the guideline of Brick model structure, BEM in a proprietary format and BMS in the customized description will be transformed into Brick models with the same structure.

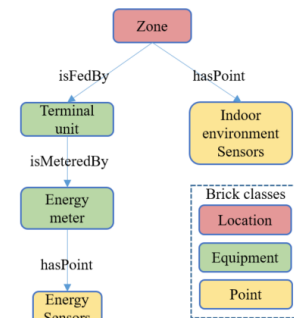


Figure 5: Brick model structure guideline.

BEM to Brick

To facilitate BEM modeling, the IFC file containing spaces and geometries is first exported from Revit and then imported into IDA-ICE after cleanup and correction using IFC tools such as abstractBIM⁸ and SimpleBIM⁹. Finally, the energy-related information is enriched directly in IDA-ICE. Once the BEM model is ready, it is possible to develop a processing tool dedicated to the proprietary format of IDA-ICE, but the developed tool cannot be generalized for other BEM tools with other proprietary formats. In this work, the method chosen was to export the building energy-related data including locations, equipment, and points in CSV format. Since the BEM tool provides a limited right for data export, the export process is semi-automatic with some data copied and pasted into the CSV file. In accordance with the brick structure guideline, the building energy data is structured in Brick using the open-source BEM2Brick tool brick-builder¹⁰.

⁶<https://www.autodesk.eu/products/revit/overview?term=1-YEAR&tab=subscription>

⁷<https://www.equa.se/en/ida-ice>

⁸<https://www.abstractbim.com/>

⁹<https://simplebim.fr/>

¹⁰<https://github.com/gtfierro/brick-builder>

BMS to Brick

The data points in customized definitions are first exported from the BMS platform EcoStruxure into a CSV file. Then they are interpreted and enriched with related BMS documents. After enrichment, they are extended as locations, equipment, and points. In the end, they are structured in a Brick model that complies with the Brick structure guideline using the open-source BMS2Brick tool Brickify¹¹ (a tool of the same family as brick-builder). The process is labor intensive and requires prior knowledge due to their customized definitions.

Brick unification

Brick ontology and extension From the Brick schema resources¹², the Brick ontology can be obtained in Turtle format which is understood by most Semantic Web tools. If needed Brick can be extended according to the best practices¹³. In this work, 15 new concepts including classes and relationships have been added. As shown in Figure 6, the new relationship ‘ext:vsMeanOf’ indicates that the sensed value of the subject should be compared with the mean sensed value of the objects, and it serves to map the BEM and BMS sensors as presented in the following part Points mapping rules.

```
@prefix brick: <https://brickschema.org/schema/Brick#> .
@prefix ext: <https://example.com/schema/BrickExtension#> .
ext:vsMeanOf a owl:ObjectProperty ;
  rdfs:subPropertyOf brick:hasPart ;
  skos:definition "The sensed value of the subject should be compared with the mean sensed value of the objects" ;
  rdfs:domain ext:VirtualSensor ;
  rdfs:range brick:Sensor .
```

Figure 6: Example of Brick concept extension in Turtle format.

Locations mapping rules The zoning between BEM and BMS is different as one HVAC zone in BEM may contain multiple zones of controls in BMS. Here the zoning mapping rule is based on a script manually created according to the BEM and BMS related documents. As shown in Figure 7, the BEM zone ‘C_F3_04_15_Circulation’ includes (brick:hasPart) multiple BMS zones such as ‘C_F3_100’. And ‘C2_F3_12_Open_Space’ is the same as (owl:sameAs) ‘C_F3_012’.

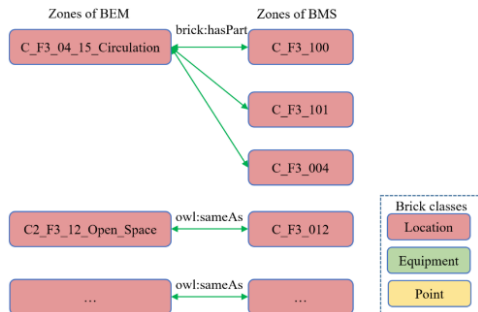


Figure 7: Zone mapping between BEM and BMS.

¹¹<https://brickschema.readthedocs.io/en/latest/brickify/index.html>

¹²<https://brickschema.org/resources>

Equipment mapping rules Based on the Brick model structure guideline, equipment of the same type serving two mapped zones will be automatically mapped with an appropriate relationship such as ‘owl:sameAs’ indicating two equivalent equipment. As shown in an example in Figure 8, ‘bldg: C_F3_012_Terminal’ from BEM and ‘bldg:3400’ from BMS belong to the same Brick class ‘brick: Radiant_Ceiling_Panel’, and they serve two mapped zones ‘C2_F3_12_Open_Space’ and ‘C_F3_012’, they can be automatically mapped as equivalent terminals with the relationship ‘owl:sameAs’. This rule can be generalized to other Brick models based on the same Brick model structure guideline.

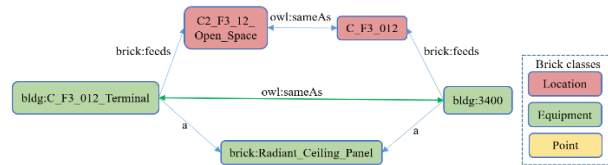


Figure 8: Example of equipment mapping between BEM and BMS.

Points mapping rules Once the locations and equipment mapping are done points mapping can be automatically done based on their type and location or related equipment. For instance, if two zone air temperature sensors, one from BEM and another from BMS, are linked to two mapped zones, then the two sensors can be automatically mapped with an appropriate association. It may happen that multiple BMS sensors correspond to one BEM sensor as shown in Figure 9 for the temperature sensor, which leads to difficulties in performing gap verification. In this case, it is proposed to compare the average of the temperature sensed by multiple BMS sensors to the value sensed by one BEM sensor, so the BEM sensor (on the left) is linked to the BMS sensors (on the right) with an extended relationship ‘ext:vsMeanOf’ (the sensed value of the subject should be compared with the mean sensed value of the objects). The points mapping rules can be generalized to other Brick models based on the same Brick model structure guideline.

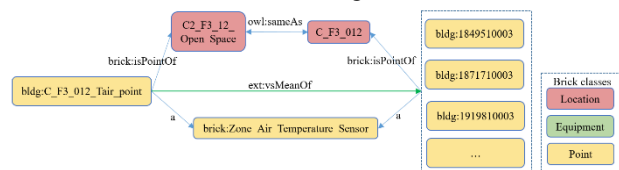


Figure 9: Example of points mapping between BEM and BMS.

Brick inference rules As the Brick model may be queried using different predicates and classes, to make it easier to use, some information is automatically added by applying Brick inference rules¹⁴. The information helps facilitate efficient queries and mainly includes Inverse relationships and Superclasses.

¹³<https://docs.brickschema.org/extra/extending.html>

¹⁴<https://brickschema.readthedocs.io/en/latest/inference.html>

Unifier Based on the open-source tools brickschema¹⁵ and pystardog¹⁶, a ‘unifier’ has been developed using Python language to unify two or more different Brick models. The unifier takes as input the Brick ontology and extension, the Brick models, and the different rules, and outputs a unified Brick model.

Graph data and Time series storage

The graph data is intuitive for the user, and flexible to add new nodes and relationships between nodes. Moreover, it can support collaborative filtering with the standard query language SPARQL, various interesting graph algorithms, etc... After the rule-based Brick unification process, the unified Brick model is stored in a graph database Stardog¹⁷. And the simulated and measured time series are directly stored in a SQL database MySQL¹⁸. Using SPARQL and SQL queries, the targeted space or equipment with its simulated or measured time series can be retrieved to perform the gap verification between its expected and actual performance.

Results

Based on the data interoperability framework, the metadata and time series can be queried to perform the gap verification between the building’s expected and actual performance. At the time of writing, the time series managed by BMS in the building is not accessible. Therefore, the BMS time series are generated by changing some energy-related parameters of the BEM model in IDA-ICE. For ease of implementation, the changed parameters mainly include indoor temperature setpoints, heating and cooling efficiencies, and internal gains. Here an open workspace is chosen as a sample space to show some results of this work. Figure 10 shows the gap verification of the zone air temperature between BEM and BMS in the sample space. In Figure 11, the gap between BEM and BMS for heating and cooling power in the same sample space is also performed based on the queried data. The anomaly of the curves in the interval of 6000-8000 hours is due to the lack of outdoor climate measurement data during this period.

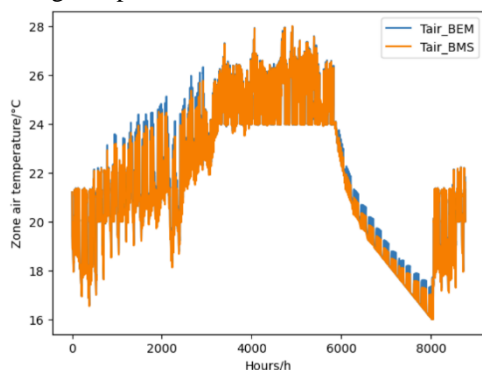


Figure 10: Zone air temperature gap between BEM and BMS in an open workspace.

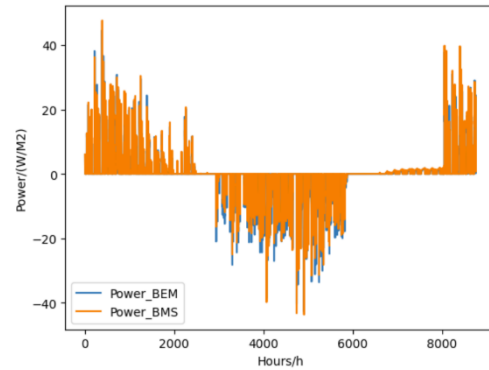


Figure 11: Power gap between BEM and BMS for heating (on the ends) and cooling (in the middle) in an open workspace.

The objective here is to show the feasibility of the performance gap verification with the proposed framework rather than fault detection and diagnosis which will be investigated in future work with real BMS-collected data.

Discussion

In this work, a data interoperability framework has been proposed to achieve BEM and BMS data interoperability. This framework is viable in real-world implementation based on available open-source tools, ontology, and semantic web technologies. However, some issues need to be pointed out. The first one concerns the process from BEM to Brick, which is not straightforward due to the proprietary BEM format. The second problem relates to the customized representation of BMS data, which makes the interpretation of BMS data time-consuming. The above problems can be solved by adopting W3C standards to make BEM and BMS data interoperable such as standardizing the BMS data representation in Brick.

Conclusion

Digitization in the building industry leads to heterogeneous data sources in the building life cycle. Ontology and semantic web technologies enable data interoperability with a consistent semantic representation of different data sources. In this work, a data framework has been proposed that enables the gap verification between the expected and actual performance of a building. Based on semantic web technologies and Brick ontology, this framework enables the interoperability of data from heterogeneous data sources, especially BEM and BMS. This work provides the building engineers with a viable framework for data interoperability as a first step toward a service-oriented digital twin. They can extend the framework with other data sources and services as needed. Future work will focus on enriching the Brick database and the diversity of services.

¹⁵<https://brickschema.readthedocs.io/en/latest/index.html>

¹⁶<https://pystardog.readthedocs.io/en/latest/pdf/>

¹⁷<https://www.stardog.com/>

¹⁸<https://dev.mysql.com/>

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References

- Chamari, L., Petrova, E., Pauwels, P., 2022. A web-based approach to BMS, BIM and IoT integration: a case study. *CLIMA* 2022 Conf. <https://doi.org/10.34641/clima.2022.228>
- Clausen, A., Arendt, K., Johansen, A., Sangogboye, F.C., Kjærgaard, M.B., Veje, C.T., Jørgensen, B.N., 2021. A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings. *Energy Inform.* 4, 40. <https://doi.org/10.1186/s42162-021-00153-9>
- Djuric, N., Novakovic, V., 2009. Review of possibilities and necessities for building lifetime commissioning. *Renew. Sustain. Energy Rev.* 13, 486–492. <https://doi.org/10.1016/j.rser.2007.11.007>
- Elagiry, M., Charbel, N., Bourreau, P., De Angelis, E., Costa, A., 2020. IFC to Building Energy Performance Simulation: A systematic review of the main adopted tools and approaches.
- Fierro, G., Koh, J., Agarwal, Y., Gupta, R.K., Culler, D.E., 2019. Beyond a House of Sticks: Formalizing Metadata Tags with Brick, in: *Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*. Presented at the BuildSys '19: The 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, ACM, New York NY USA, pp. 125–134. <https://doi.org/10.1145/3360322.3360862>
- Fierro, G., Prakash, A.K., Mosiman, C., Pritoni, M., Raftery, P., Wetter, M., Culler, D., 2020a. Interactive Metadata Integration with Brick. pp. 344–345. <https://doi.org/10.1145/3408308.3431125>
- Fierro, G., Prakash, A.K., Mosiman, C., Pritoni, M., Raftery, P., Wetter, M., Culler, D.E., 2020b. *Shepherding Metadata Through the Building Lifecycle*, in: *Proceedings of the 7th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*. Presented at the BuildSys '20: The 7th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, ACM, Virtual Event Japan, pp. 70–79. <https://doi.org/10.1145/3408308.3427627>
- Gunay, B., Bursill, J., Huchuk, B., Shillinglaw, S., 2022. Inverse model-based detection of programming logic faults in multiple zone VAV AHU systems. *Build. Environ.* 211, 108732. <https://doi.org/10.1016/j.buildenv.2021.108732>
- Hosamo, H.H., Imran, A., Cardenas-Cartagena, J., Svennevig, P.R., Svidt, K., Nielsen, H.K., 2022. A Review of the Digital Twin Technology in the AEC-FM Industry. *Adv. Civ. Eng.* 2022, 1–17. <https://doi.org/10.1155/2022/2185170>
- Hu, S., Wang, J., Hoare, C., Li, Y., Pauwels, P., O'Donnell, J., 2021. Building energy performance assessment using linked data and cross-domain semantic reasoning. *Autom. Constr.* 124, 103580. <https://doi.org/10.1016/j.autcon.2021.103580>
- Jradi, M., Arendt, K., Sangogboye, F.C., Mattera, C.G., Markoska, E., Kjærgaard, M.B., Veje, C.T., Jørgensen, B.N., 2018. ObepME: An online building energy performance monitoring and evaluation tool to reduce energy performance gaps. *Energy Build.* 166, 196–209. <https://doi.org/10.1016/j.enbuild.2018.02.005>
- Katsigarakis, K.I., Giannakis, G.I., Lilis, G.N., Rovas, D.V., 2019. An IFC data preparation workflow for building energy performance simulation, in: *Computing in Construction*. Presented at the 2019 European Conference on Computing in Construction, University College Dublin, pp. 164–171. <https://doi.org/10.35490/EC3.2019.188>
- Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., Holmström, J., 2019. Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings. *IEEE Access* 7, 147406–147419. <https://doi.org/10.1109/ACCESS.2019.2946515>
- Luo, N., Pritoni, M., Hong, T., 2021. An overview of data tools for representing and managing building information and performance data. *Renew. Sustain. Energy Rev.* 147, 111224. <https://doi.org/10.1016/j.rser.2021.111224>
- Malhotra, A., Bischof, J., Nichersu, A., Häfele, K.-H., Exenberger, J., Sood, D., Allan, J., Frisch, J., Treeck, C., O'Donnell, J., Schweiger, G., 2021. Information modelling for urban building energy simulation—A taxonomic review. *Build. Environ.* <https://doi.org/10.1016/j.buildenv.2021.108552>
- Mills, E., 2011. Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States. *Energy Effic.* 4, 145–173. <https://doi.org/10.1007/s12053-011-9116-8>
- Mohajer, M.F., Aksammija, A., 2019. Integration of Building Energy Modeling (BEM) and Building Information Modeling (BIM): Workflows and Case Study. <https://doi.org/10.7275/BN9J-E183>
- Nytsch-Geusen, C., Kaul, W., Rädler, J., Shenoy, V., Balekai, P., 2019. The Digital Twin As A Base For

The Design Of Building Control Strategies. Presented at the Building Simulation 2019, Rome, Italy, pp. 4141–4148.

<https://doi.org/10.26868/25222708.2019.210389>

Opoku, D.-G.J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., Bamdad, K., 2022. Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. *Buildings* 12, 113. <https://doi.org/10.3390/buildings12020113>

Pauwels, P., Fierro, G., 2022. A Reference Architecture for Data-Driven Smart Buildings Using Brick and LBD Ontologies. *CLIMA 2022 Conf.* <https://doi.org/10.34641/clima.2022.425>

Roa, C.D., Raftery, P., Sun, R., Paul, L., Prakash, A.K., Pritoni, M., Fierro, G., Peffer, T., 2022. Towards a Stronger Foundation: Digitizing Commercial Buildings with Brick to Enable Portable Advanced Applications. <https://doi.org/10.20357/B7ZG6R>

Taye, M., 2010. Understanding Semantic Web and Ontologies: Theory and Applications. *J. Comput.* 2.

Torabi, N., Gunay, H.B., O'Brien, W., Barton, T., 2022. Common human errors in design, installation, and operation of VAV AHU control systems – A review and a practitioner interview. *Build. Environ.* 221, 109333. <https://doi.org/10.1016/j.buildenv.2022.109333>

Wu, W., Issa, R.R.A., 2012. BIM-Enabled Building Commissioning and Handover. *Comput. Civ. Eng.* 2012.

Zhan, S., Chong, A., Lasternas, B., 2020. Automated recognition and mapping of building management system (BMS) data points for building energy modeling (BEM). *Build. Simul.* 14, 1–10. <https://doi.org/10.1007/s12273-020-0612-7>