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Extending the Brick schema to represent metadata of occupants

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ABSTRACT

Energy-related behaviors of occupants constitute a key factor influencing building performance; accordingly, the measured occupant data can support the objective assessment of the indoor environment and energy performance of buildings, which can inform building design and operational decisions. Existing data schemas focus on metadata of sensors, meters, physical equipment, and IoT devices in buildings; however, they are limited in representing the metadata of occupant data, including occupants' presence in spaces, movement between spaces, interactions with building systems or IoT devices, and preference of indoor environmental needs. To address this gap, an extension to the widely adopted metadata schema, Brick, is proposed to represent the contextual, behavioral, and demographic information of occupants. The proposed extension includes four parts: (1) a new "Occupant" class to represent occupants' demography and energy related behavioral patterns, (2) new subclasses under the Equipment class to represent envelope system and personal thermal comfort devices, (3) new subclasses under the Point class to represent occupant sensing and status, and (4) new auxiliary properties for occupant interactable equipment to represent the level of controllability for each piece of equipment by occupants. The extension is implemented in the Brick schema and has been tested using multiple occupant datasets from the ASHRAE Global Occupant Database. The extension enables Brick schema to capture diverse types of occupant sensing data and their metadata for FAIR data research and applications.

1. Introduction

1.1. Background

The interactions between building occupants and their surrounding environments play a deliberate and important role in building performance and energy use, as well as in occupants' comfort, health, and productivity [1,2]. Previous research indicate that occupants' thermally adaptive behaviors (e.g., opening windows, adjusting thermostat/personal devices) are strongly tied to space heating and cooling loads, which account for 37% and 54% of total site energy use in commercial and residential buildings, respectively, in the United States [3]. Despite the high energy use of heating, ventilation and air conditioning (HVAC) systems to provide a comfortable indoor environment, about 35% of building occupants are unsatisfied with code-defined indoor environmental conditions in commercial buildings [4,5]. This usually leads to the occupants' adjustment of local thermostat settings or HVAC equipment, which can further yield overall dissatisfaction within the entire thermal zone, as well as an increase of energy consumption [6,7]. Therefore, investigating the human-building interaction (HBI) to help achieve an optimized status of both occupant comfort and energy consumption has been a hot topic of research in recent decades [8–11].

The current investigations of occupants' adaptive behavior generally rely on two approaches: (1) developing occupant behavior models for integration with whole building energy simulation, and (2) collecting the longitudinal data of occupant adaptive behaviors, occupants'

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; BPS, Building Performance Simulation; DNAS, Drivers, Needs, Actions, Systems; EBC, Energy in Buildings and Communities; FAIR, Findable, Accessible, Interoperable, and Reusable; HBI, Human Building Interaction; HVAC, Heating, Ventilation and Air Conditioning; IEA, International Energy Agency; IoT, Internet of Things; LBNL, Lawrence Berkeley National Laboratory; NREL, National Renewable Energy Laboratory; obXML, occupant behavior eXtensible Markup Language; ORNL, Oak Ridge National Laboratory; PNNL, Pacific Northwest National Laboratory; ppm, parts per million; VAV, Variable Air Volume.

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thermal comfort, and building performance parameters via in-situ experiments and surveys. Regression-based models are commonly used to describe the group-level probability of an adaptive behavior given certain thermal conditions in the last decade [12,13]; while agent-based models have been explored in the recent decade to address the limitations of previous regression models, by representing individuals as autonomous "agents" with attributes, attitudes, and rules of interactions with other agents and their surrounding environments [14,15]. On the other hand, many longitudinal field studies have been conducted to collect occupant and indoor environmental data, supporting explorations of the HBI mechanism through traditional statistical methods or machine learning algorithms [16–18]. These measured datasets can also serve as the ground truth data for evaluating or validating regression-based or agent-based models [19,20]. Previous longitudinal field studies have focused on the environmental determinants of occupants' discomfort and behavior, while recent surveys and experiments have tended to explore more personal determinants, such as occupants' motivations and attitudes, as well as the locus of control [21].

Either of the aforementioned approaches require the use of occupant data — either measured data, survey data, or synthetic data generated from simulation. The data points include occupant data, indoor and outdoor environmental data, building and system operational data, and energy meter data. As the data have increased in volume, lack of consistency in representation, format, and meaning of these data has become evident and problematic. Metadata are descriptions of data which provide contextual information and thus assist in the discovery of that data on behalf of applications and other data consumers. A recent review of existing data schemas and tools indicates that some data schemas, such as Brick and Green Button, are capable of representing the metadata of indoor environmental data, building and system operational data, and meter data [22]. However, ontologies or schemas representing occupant data (especially their metadata) are very limited, which hinders the use of the data to gain a deeper understanding of HBI and associated insights to improve building design and operations.

1.2. Existing data schemas on occupants

Luo's review [22] covers existing data schemas for occupants. Two essential ones are discussed here.

As part of Annex 66's efforts [23], under the International Energy Agency's (IEA's) Energy in Buildings and Communities (EBC) Programme, Mahdavi and Taheri [24] developed an ontology to represent and incorporate multiple layers of data information obtainable from different categories of building monitoring systems, which can be used to support and streamline building data acquisition, storage, and processing in multiple computational applications. The ontology is grounded on the identification of six basic data categories, namely: inhabitants, indoor and outdoor environmental conditions, control systems and devices, equipment, and energy flows. Sensors, meters, and other data sources (e.g., simulated virtual sensors and human agents) in the aforementioned six categories generate streams of information (values of corresponding variables) subject to monitoring, storage, and processing. Given each data category and the respective subcategories, monitored variables are specified in terms of their values, associated sources, and possible actors.

Currently, this ontology is highly theoretical, with pilot implementation for a few datasets [25,26]. Fig. 1 illustrates the overview of monitored building, environment, and occupant variables in a longitudinal field study [25] that utilized this Annex 66 ontology. One limitation lies in the hierarchical structure of this ontology, which is less flexible and expressive compared with other data schemas. Specifically, the ontology only captures minimal contextual information about the building, such as what kind of HVAC system is installed and where sensors are located. Therefore, it is not comprehensive enough to represent occupants' interactions with systems, equipment and devices, which are essential elements to collect during occupant-related physical measurements and surveys.

Another effort is the development of the DNAS (Drivers, Needs, Actions, Systems) framework and obXML schema by Dr. Tianzhen Hong of Lawrence Berkeley National Laboratory (LBNL). obXML [27] is an XML formatted schema to represent the occupant behavior in buildings, which facilitates the integration with building information modeling and building performance simulation. The topology of the schema follows the DNAS framework [28], which describes the mechanism of multiple adaptive behaviors in four key elements: (1) Drivers representing the environmental factors; (2) Needs representing the physical and nonphysical requirements of occupants to ensure the satisfaction with their environments; (3) Actions representing interactions between occupants and building systems; and (4) Systems representing the corresponding equipment where occupants may interact for maintaining thermal comfort. Related data points of these four key elements include occupant presence, occupant attributes and attitudes, system and equipment status, and other building and system operational data.

To enhance the interoperability of obXML in broader applications and use cases across the building life cycle, Putra and Hong et al. [29] proposed an extension of the original DNAS framework for representing the synthetic occupant population. The extensions introduce new elements to the existing framework that describe more elaborate characteristics of an occupant-agent or a group-of-agents for agent-based modeling applications.

The DNAS framework and its obXML schema were used in simulation studies [1,30,31] to demonstrate their interoperability between occupant behavior models and building energy models. However, obXML is designed to represent occupant behavior models for use in simulation especially for co-simulation with building energy modeling tools such as EnergyPlus. It focuses specifically on the mechanism of multiple adaptive behaviors to better predict the probability of certain occupant behaviors. Therefore, it falls short in representing the metadata of occupant data collected from physical measurements, virtual sensing, or surveys for data-driven analysis. Similar to the aforementioned limitation of the Annex 66's ontology, obXML schema doesn't capture contextual information about the building and system, as well as the interactions between occupants and systems.

1.3. Brick schema

Brick [32] is an open source ontology developed by a consortium of researchers and industry representatives to standardize semantic descriptions of the physical, logical, and virtual assets in buildings and the relationships between them.[1] It provides an extensible dictionary of terms and concepts, a set of relationships for linking and composing concepts together, and a flexible data model [33] based on semantic web technologies. Brick represents the data sources and their context as a directed graph. Fig. 2 illustrates an example of a Brick model [34]. It depicts an air handling unit (AHU) supplying air to a variable air volume (VAV) box that conditions a thermal zone composed of two rooms. In one of these rooms a networked lighting system is also installed (luminaire). Brick is in active open development supported by academic institutions, federal agencies, and industry. Reference implementations of Brick tools, as well as building data, are free and permissively licensed.

Equipment, sensors and actual "things" in buildings are represented as entities in the Brick model. Each entity is an instance of a certain class and can have relationships with other entities. The classes and subclasses are defined under an extensible hierarchy (as shown in Fig. 3) for flexible usage, connected by various canonical relationships, such as *hasLocation* and *isLocationOf*, *hasPart* and *isPartOf*, and *feeds* and *isFedBy*.

The current version of the Brick schema (v1.2, released Feb 2020) includes four main classes:

[1] Brick: A uniform metadata schema for buildings. https://brickschema.org

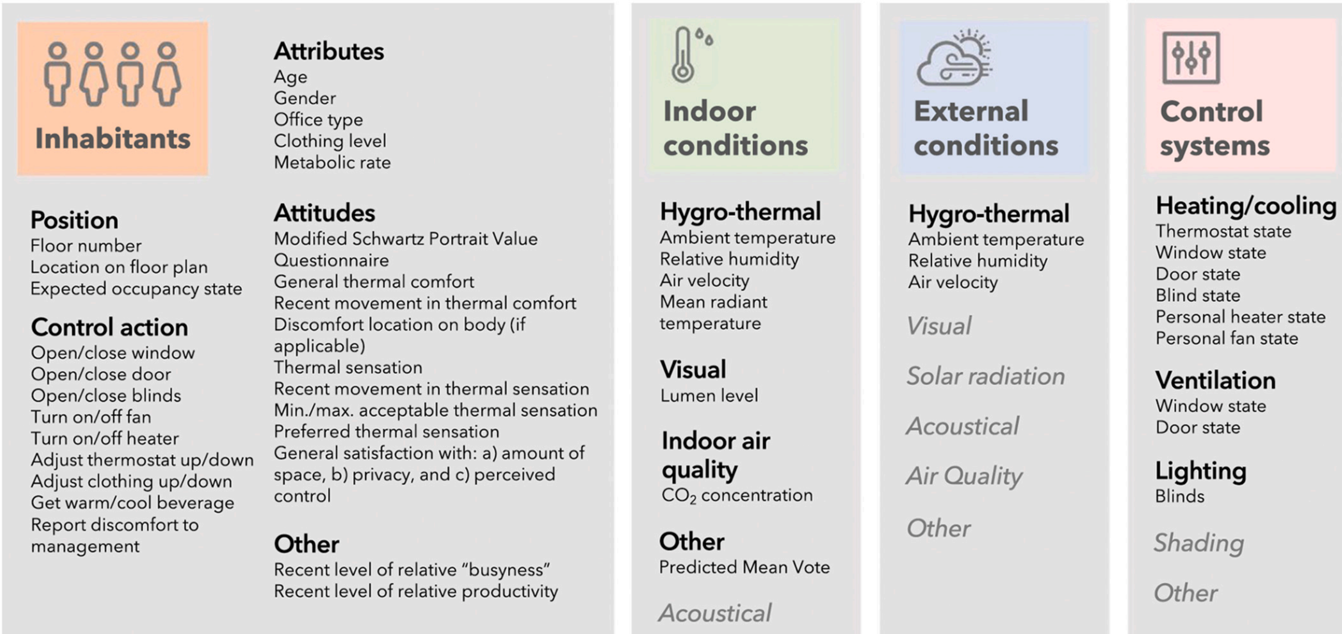

Fig. 1. Overview of the monitored building, environment, and occupant variables. Variables are organized according to the data categorization in the ontology by Mahdavi and Taheri [24]. (adopted from [25]).

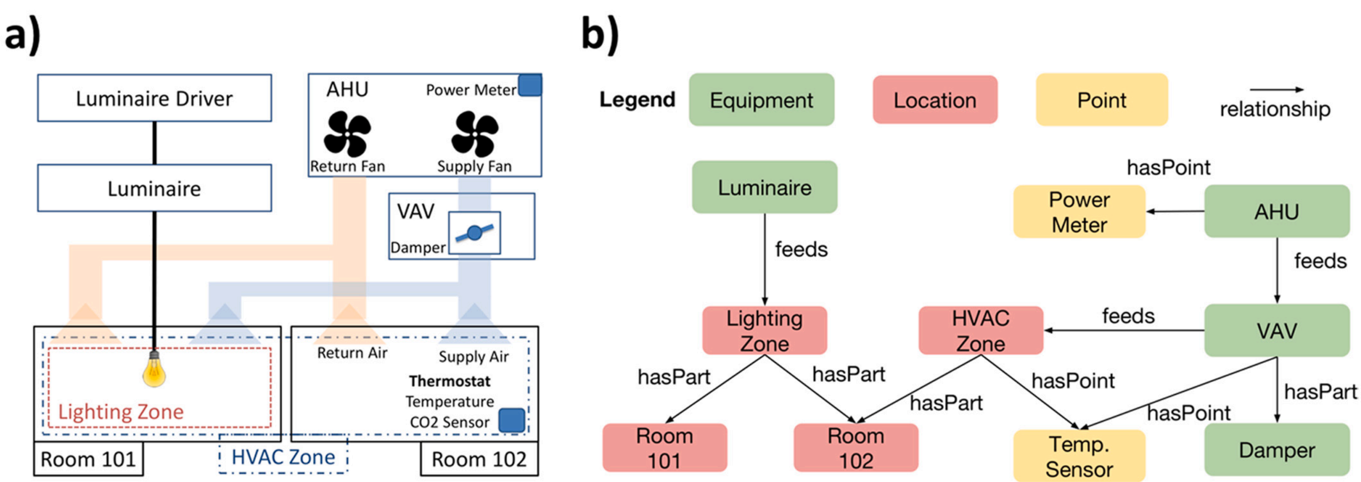

Fig. 2. Example of a Brick model: a) Example building, b) Example building modeled in Brick (visualized) [34].

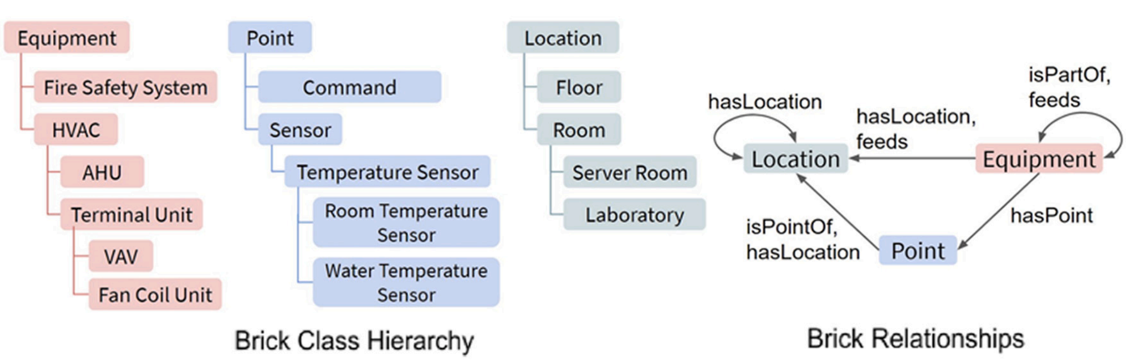

Fig. 3. Brick class hierarchy and relationships.

- *Equipment* - representing devices that serve all or part of the building and may include electric power, lighting, transportation, or service water heating, including, but not limited to, furnaces, boilers, air conditioners, heat pumps, chillers, water heaters, lamps, luminaires, ballasts, elevators, escalators, or other devices or installations.
- *Location* - representing the physical and logical location of equipment and sensors, including building, floor, space, and zone as the subclasses.
- *Measurable* - describing the quantity and substance of the equipment and sensors.
- *Point* - describing the information of sensors (an input point that represents the value of a device or instrument designed to detect and measure a variable); setpoint (an input value at which the desired property is set); status (an input point that reports the current operating mode, state, position, or condition of an item); command (an output point that directly determines the behavior of equipment and/or affects relevant operational points); and parameter (configuration settings that are used to guide the operation of equipment and control systems).

The Brick schema has been adopted by more and more studies and applications [35,36], proving it is capable of representing the metadata of equipment and sensors, as well as organizing the data points of system operational data in a structured and expressive way. Brick's representation of the composition and topology of building subsystems enables the rich contextualization of the occupant-related metadata, which is the focus of this paper.

1.4. Contributions

The proposed extension to the Brick schema describes the contextual, demographic, and behavioral information of occupants and their related data, including occupant information (i.e., occupancy, attributes, attitudes) and occupant adaptive behaviors (i.e., adjusting thermostat, opening windows). The extension was built upon previous occupant ontology and schemas but adds significant new semantic representations in the Brick schema through an open source code at GitHub. The data coverage of the extension was tested using two datasets from the ASHRAE Global Occupant Database.[2] The extended Brick schema was demonstrated to create a metadata model for a monitored dataset of a medium-sized office building with occupant data. The extension, together with other new features of Brick schema, will enable its broad adoption in research and applications of grid-interactive efficient buildings which includes an essential aspect of occupant comfort and health, as well as human-building interactions.

2. Method

This section first summarizes the topology of occupant data and describes the metadata of an occupant's monitored data to capture the contextual, demographic, and behavioral information, including occupant presence, occupant attributes and attitudes, and occupant adaptive behaviors interacting with buildings and systems. The section then develops a plan to extend the Brick schema to address the identified gaps with respect to occupant metadata.

2.1. Metadata of occupant data

There are three primary approaches to collecting occupant data: (1) monitored information from data acquisition and sensing technologies, (2) reported information by surveys, and (3) simulated information from building performance simulation (BPS) [37]. Sensing and data acquisition technologies are used to collect a large volume of granular occupant data, including occupant count and occupants' interactions with buildings and systems, under either in-situ or laboratory conditions [18]. Surveys relying on telephone, paper, or online services are used to collect occupant preferences (e.g., thermal and visual comfort sensation, clothing level) and occupant social demographics (e.g., occupant attributes and social interactions), where measurements are hard to get [25,38]. The simulated occupant data are similar to the monitored data, but can include more samples under extreme conditions and applications [19,39].

The typology of occupant data can be summarized into three categories: (1) occupancy (e.g., space occupied status, number of occupants, occupant location, and occupancy proxy information such as Wi-Fi access point counts and carbon dioxide [CO_2] concentration); (2) occupant actions, such as interactions with building and energy systems (e.g., open/close windows, pull up/down blinds, dim or turn on/off lights, turn on/off plug-in equipment); and (3) occupant demographic and contextual information, such as attributes (e.g., gender, age, country) and attitudes (e.g., thermal preference and sensations). Table 1 shows the typology of the occupant data.

The metadata of occupant data refers to occupants' attributes (e.g., contextual information of occupants, such as gender, age, location) and attitudes (e.g., behavioral information, such as clothing style and thermal preference), during the data collection of surveys and occupant related physical measurements, such as occupant count sensing and indoor air quality sensing.

2.2. Extension to the Brick schema

We propose four aspects to extend the Brick schema, based on the three categories of occupant data in Table 1. Fig. 4 illustrates the high-level concept of the extension plan.

- A new class, *Occupant*, to represent occupants of the building, relevant demographic and physiological information, and the relationships between occupants and the building

The new *Occupant* class is a sibling of the other root Brick classes: *Equipment* representing the metadata of different systems; *Point* representing the metadata of sensors, meters, and status; and *Location* representing the spatial position of equipment, sensors, and occupants. Entities under the new *Occupant* class can be associated with other entities under *Location* and *Equipment* classes via relationships such as *hasAssignedLocation* and *hasAccessTo,* respectively. The new *Occupant* class encapsulates two subclasses: *Individual*, representing a single occupant, and *Group*, representing a group of occupants. This permits the distinction of surveyed properties that apply to a collection of individuals and those that apply to a single individual. A group can be associated with an individual, using the property of *isMemberOf* and *hasMember* inversely. The number of individuals within a group is also indicated using the property of *groupSize*. The *Occupant* class also defines a set of demographic and physiological properties defined in Table 1; these are optional properties which are associated with individuals or groups of occupants.

- New subclasses under the *Equipment* class, to represent occupant behavior related systems and devices

The majority of occupant behaviors consist of occupants' adjustments to different equipment and systems, yielding updates of status to these devices. Some equipment or systems that occupants can access, such as the thermostat and lighting system, already exist under the current Brick schema, while others, such as windows, doors, and personal devices (e.g., personal heater, desktop fan) do not. To better represent the occupants' interactions with the buildings and systems, the extension augments the Brick *Equipment* class list with common

[2] ASHRAE Global Occupant Behavior Database. https://ashraeobdatabase.com

Table 1
Typology of occupant data.

Category	Attributes	Description
Occupancy	Presence	A binary status of whether a space is occupied or unoccupied
	Number of people	Occupant count of a space
	Assigned location	A regular space/room/office in which an occupant resides
	Location	A time varying location (space) where an occupant stays
	Wi-Fi connected device count	Occupancy proxy information - Number of connected devices
	CO_2 concentration	Occupancy proxy information - CO_2 concentration (ppm) of a space
	Thermostat adjustment	Occupants adjust a thermostat, which changes the thermostat status (e.g., mode, setpoint)
	Window operation	Occupants operate a window, which changes the window status (e.g., open, closed, degree of openness)
	Door operation	Occupants operate a door, which changes the door status (e.g., open, closed, degree of openness)
	Blind operation	Occupants operate a blind, which changes the blind status (e.g., open, closed, stage)
	Lighting operation	Occupants operate lighting, which changes the lighting status (e.g., on, off, degree of dimming)
	Ceiling fan operation	Occupants operate a ceiling fan, which changes the ceiling fan status (e.g., on, off, stage)
	Portable heater operation	Occupants operate a portable heater, which changes the portable heater status (e.g., on, off, stage)
	Air conditioning operation	Occupants operate an air conditioner, which changes the air conditioning status (e.g., on, off, stage)
	Computer operation	Occupants operate a computer, which changes the computer status (e.g., on, off)
	Clothing change	Clothing change activity of an occupant
	Clothing insulation	Clo value or range
	Thermal sensation	Personal sensation of the thermal environment
	Activity level	Activity level of an occupant
	Metabolic rate	Metabolic rate of an occupant
Action	Drink	If the occupant drinks beverages or not (binary value)
Occupant demographic and contextual information	Gender	Surveyed gender of an occupant
Attributes	Age	Exact value or range
	Body mass index	A value derived from the mass and height of a person
	Ethnicity	Surveyed ethnicity of an occupant
	Climate zone	Climate zone corresponding to the city and country
	City	Which city the occupant(s) live in when the data are collected
	Country	Which country the occupant(s) live in when the data are collected
	Clothing style	Description of clothing or choices of Casual or Business attire
Attitudes	Thermal preference	Personal choice of warmer, cooler, or neutral temperature based on the ASHRAE thermal comfort zone

personal devices. The *hasAccessTo* relationship indicates which members of the *Occupant* class are relevant to the device under the *Equipment* class.

- New subclasses under the *Point* class, to represent occupant related sensors and status

The current Brick ontology is capable of representing a large and growing variety of sensors and statuses (e.g., CO_2 sensors and lighting status). Some of these can be associated with certain occupant behaviors; however, other sensors for monitoring the occupant presence (e.g., Wi-Fi access point) or the status of occupant interactive systems (e.g., window status) are absent in Brick's current release. The extension supplements Brick with new subclasses of sensors and status under the *Point* class to address these occupancy-related data sources. The existing *hasPoint* relationship associates these entities with *Equipment* and *Locations* instances.

Results of occupant actions may be captured indirectly by changes in the state of a device (captured by Brick *Status* instances). In many cases it is important to know which actions were directly the result of an occupant. For this reason, we add a new type of *Point* class, *OccupantActionStream*, to represent a sequence of actions by an occupant on a piece of equipment over time. Instances of *OccupantActionStream* can be linked to both an *Equipment* and an *Occupant* instance.

- A new set of properties to represent the accessibility and controllability of equipment by occupants

Occupants may have various degrees of controllability for different equipment and devices. The adjustment to devices differs in degrees, such as binary switches, continuous switches, and fixed status, etc., which should be indicated in the metadata of the devices. Devices may be located in different types of rooms with certain privilege instructions, thus yielding various levels of occupant accessibility to the devices. For instance, occupants in an open office have to share the authority of adjusting the thermostat while not being allowed to adjust other devices. This information should be described clearly in the metadata, as should whether devices are controlled manually, automatically, or dynamically (such as being based on a grid signal). The extension defines a small set of properties to capture the controllability and accessibility of *Equipment* entities in the model.

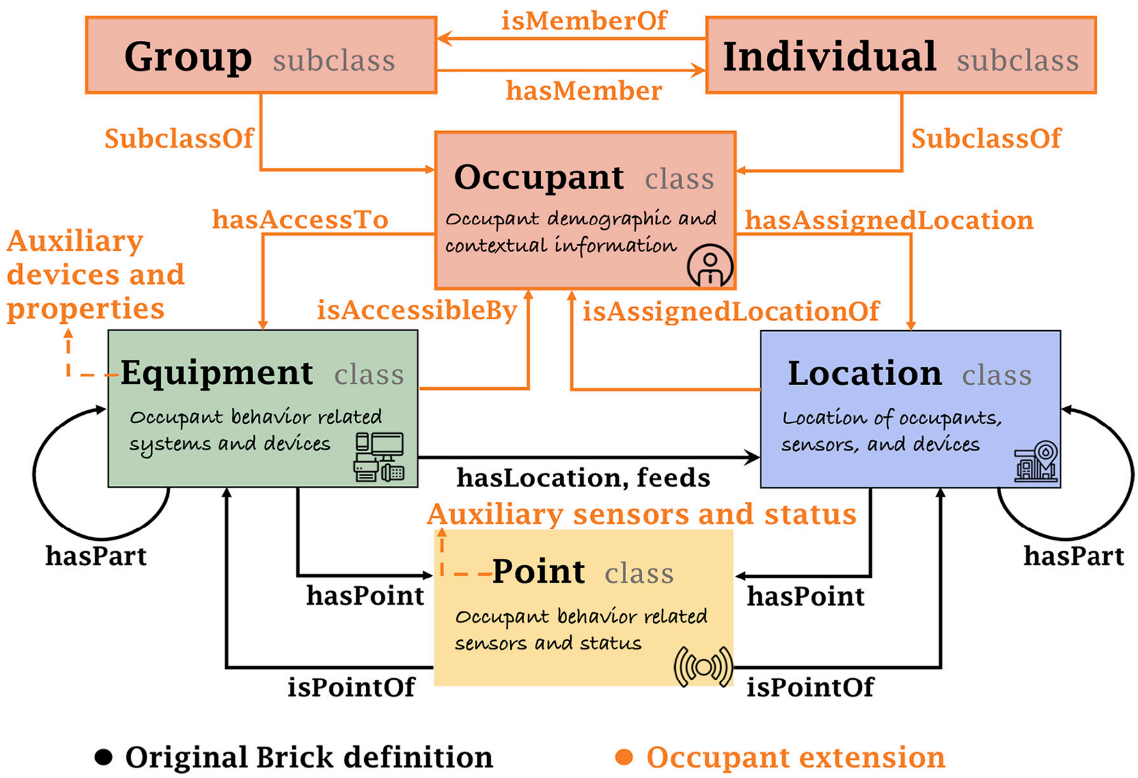

Fig. 4. Illustration of the Brick extension

3. Results

Built upon the current hierarchy of the Brick structure, we implemented the following extension to represent different categories of occupant data in the Brick schema. Fig. 5 highlights the extension in four aspects.

3.1. The new occupant class

Location, Equipment, and Point are three existing classes in Brick. In parallel with these classes, we add a new class called *Occupant*. This class represents the building occupant, which can be an individual occupant (a subclass called "*Individual*") or a group of individuals (a subclass called "*Group*") sharing some common attributes. The extension captures two kinds of properties for occupants:

1) *Attributes* - representing the characteristics of the occupant(s), such as *Gender*, *Age Range,* and *Ethnicity*.
2) *Attitudes* - representing the behavior pattern of the occupant(s), such as *Clothing Style*, *Thermal Preference* (neutral, warmer, cooler, or no preference), and *Sensations* (activity and metabolic rate).

These properties can be ascribed to an individual or a group. The subclasses of Individual and Group can both have any or all of the properties associated with an Occupant. In addition, a group property called "occ:groupSize" is used to identify the number of individuals in a group. Another two group properties include "occ:hasMember" and "occ:isMemberOf." These are used to describe the relationship between individuals and groups if this information is captured in the dataset. Individuals can be members of multiple groups, and groups can additionally be members of other groups. This enables modeling of different organizational structures.

One design challenge for the ontology is the modeling of different enumerations. While we have taken a particular stance on some of these, it is important for the ontology to support the description of datasets that are not limited to our prescribed set of definitions. For this reason the ontology supports the creation of ad-hoc enumerations that are defined in terms of other properties. Consider the example of *AgeRange*, a property that indicates the span of ages in which a particular occupant falls. The ontology defines a standard "children" age range as occupants with an age of less than 11 years, which can be used freely by datasets.

```
occ:children_age_range a occ:AgeRange;
brick:hasUnit unit:YR;
occ:upperBound 11;
occ:lowerBound 0.
```

However, if a particular dataset's definition of children is different (e.g., less than 13 years), then that dataset can define its own age range using the *upperBound* and *lowerBound* properties.

```
custom_children_age_range a occ:AgeRange;
brick:hasUnit unit:YR;
occ:upperBound 13;
occ:lowerBound 0.
```

This flexibility promotes the interpretability of data: a consumer of a dataset can inspect the definition of an age range to determine what its bounds are, even if they were not previously aware of the enumeration. This design pattern has been adopted for most of the properties with enumerated values defined by the ontology.

Each entity under the new *Occupant* Class is also capable of linking to other entities under *Location* or *Equipment* Classes to indicate the occupants' location (*hasAssignedLocation*) and accessibility to equipment and devices (*hasAccessTo*).

3.2. The new equipment subclasses

Metadata for occupant datasets requires modeling of the devices that occupants interact with and that determine the state of their environment. The current release of Brick defines classes related to environment

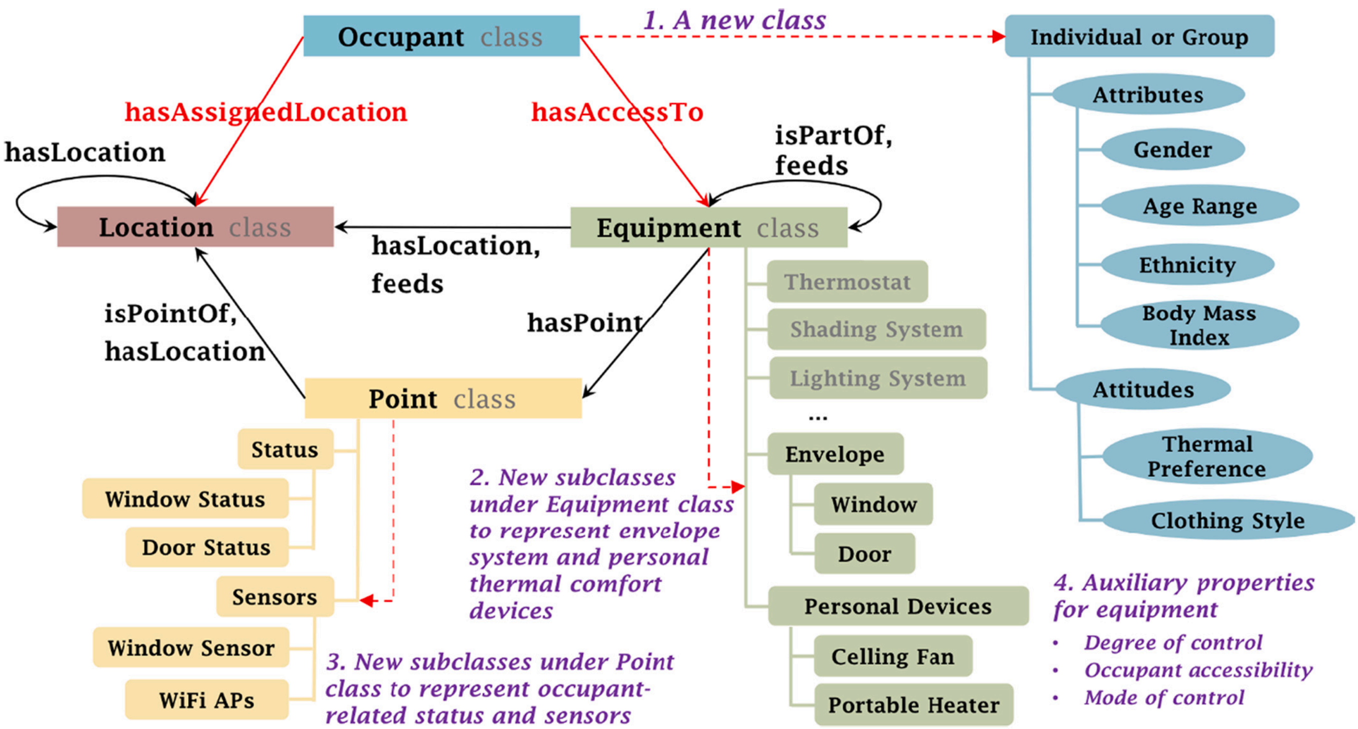

Fig. 5. Illustration of the Brick extension.

conditioning, such as *Thermostat, Shading System,* and *Lighting System*. We extend these with new subclasses corresponding to personal devices and envelope system components that occupants may interact with directly:

1) *Envelope System* - representing envelope components of a space/building that occupants may have access to, such as *Window* and *Door*
2) *Personal Devices* - representing devices that occupants may use to achieve their needs of thermal comfort, such as *Desktop Light*, *Ceiling Fan*, *Portable Fan*, and *Portable Heater*

We introduce a new relationship, *hasAccessTo*, which models either instance of the *Occupant* class (*Individual* or *Group*) that can actuate, control or access the Equipment subclass instances.

Table 2 summarizes the new subclasses under the Equipment Class, as well as the definitions of each enumeration.

Table 2
Definitions of the new subclasses of the equipment class.

Class	Subclass	Subclass	Definition
		/	Building envelope
		Window	An opening in the wall of a building to admit light or air and that allows occupants to see out
	Envelope	Door	A hinged, sliding, or revolving barrier at the entrance of a building or a zone that allows occupants to go in and out
		/	Dedicated devices used to maintain thermal comfort for occupants
		Portable_Fan	A cord-connected appliance that is easily moved by hand from place to place to provide flowing air
		Portable_Heater	A cord-connected appliance that is easily moved by hand from place to place to provide heating
		Ceiling_Fan	A mechanical fan mounted on the ceiling of a room or space, usually electrically powered, that uses hub-mounted rotating blades to circulate air
Equipment	Personal_Device	Desktop_Light	A piece of lighting equipment on the desktop to provide illuminance

3.3. The new point subclasses

Metadata for occupant datasets should cover sensors that monitor the environment and its occupants. Brick already represents many of the relevant sensors and status indicators such as *Temperature Setpoint*, *Occupancy Sensor*, *CO_2 Sensor*, *Illuminance Sensor* and *Luminance Sensor*. These *Point* subclasses are related to equipment and locations by the *hasPoint* relationship. We augment the existing set of *Point* subclasses with several new ones to represent occupant sensors and their status:

1) *Window Status* - under the *Status* subclass, to present the status of a window as open or closed.
2) *Door Status* - under the *Status* subclass, to present the status of a door as open or closed.
3) *Lighting Status* - under the *Status* subclass, to present the status of the lighting.
4) Modify the existing *Occupancy Status* subclass – under the *Status* subclass, to represent whether the certain space/building is occupied or unoccupied.
5) *Wifi Sensor* – under the *Sensor* subclass, to represent the metadata of Wi-Fi access points.
6) *Shading* Sensor - under the *Sensor* subclass, to represent the sensors that measure the shading device status. This new subclass also can be added under the *Position Sensor* subclass.

Table 3 summarizes the new subclasses under the *Point* Class, as well as the definitions of each enumeration.

3.4. Auxiliary properties

Brick schema version 1.2 introduces Entity Properties for modeling characteristics of entities within Brick models, including the number of equipment stages, the coefficient of performance, and rated power output. We extend the set of Entity Properties to model characteristics of both equipment and occupants that are relevant to occupant data.

The set of equipment Entity Properties includes three aspects on the degree of control that occupants have over the equipment, as well as their authority over the device:

1) *Degree of control* - on/off/continuous/staged/no control(fixed)
2) *Level of occupant accessibility* - no access/locked, free to adjust, shared
3) *Mode of control* - manual/automatic/dynamic response to external signals, e.g., a pricing or carbon intensity signal from the power grid

Table 4 summarizes the new entity properties, their enumerated values and the definitions of each enumeration.

3.5. Open source code at GitHub

The Brick extension has been integrated to a GitHub repository[3] for further implementation and usage. The definition of each extended element can be visualized in the extension.ttl file, while the usage was demonstrated in the example1.ttl file. The following section elaborates how the extended Brick schema represents the occupant data collected from multiple types of sources (i.e., survey-based and sensor measurement).

4. Applications

This section is to demonstrate the performance of the extended Brick schema when representing the occupant dataset. First, to test the data coverage of the extended Brick schema, we used occupant datasets from the ASHRAE Global Occupant Database,[4] which has 34 datasets contributed by the researchers from 39 institutes in 15 different countries. Specifically, two case studies were demonstrated to prove that more occupant-related data points can be represented using the extended Brick schema than with the original version or other BIM schemas, such as the Industry Foundation Classes (IFC [40]). Adopted as an international standard, IFC was developed to represent the BIM data across the whole building life cycle, from building design, building construction, to building operation and other implementations. Based on a recent review paper, the IFC schema is also capable of representing the occupant-related data [22]. We assessed the data coverage of the IFC schema, and compared that coverage with those using the original and extended Brick schema. Besides the evaluation of data coverage, we also selected a three-year building dataset to generate the Brick model using the extended Brick schema. Results showed that the occupant-related data points can be well represented using the enhanced Brick schema.

Table 3
Definitions of the new subclasses under the point class.

Class	Subclass	Subclass	Definition
Point	Status	/	Status of the equipment
		Window_Status	Status of the windows (open, closed)
		Door_Status	Status of the doors (open, closed)
		Lighting_Status	Status of the lightings (on, off)
	Sensor	/	A Sensor is an input point that represents the value of a device or instrument designed to detect and measure a variable (ASHRAE Dictionary)
		Window_Sensor	A sensor used to monitor the status of the window (open, closed, open angle)
		WiFi_AP	A sensor used to monitor the number of connected devices for a Wi-Fi access point
		Shading_Sensor	A sensor used to monitor the status of a shading device (on, off)

Table 4
Definitions of the auxiliary properties.

Entity property	Enumerations	Definition
	/	How a device may be controlled by an occupant
	On_Off_Control	Device has on/off binary control
	Continuous_Control	Device supports a continuous range of control inputs (e.g. 0%–100%)
	Staged_Control	Device has a fixed number (> 2) of inputs
Degree_Of_Control	No_Control	Device is fixed or has no control input capabilities
	/	How accessible a device is to be controlled by occupants
	Not_Accessible	Device is inaccessible to occupants
	Adjustable	Device is accessible to occupants for adjustment
Occupant_Accessibility_Level	Shared	Device is accessible by multiple occupants
	/	The policy and algorithm under which the device is controlled
	Manual_Mode	Device is controlled manually
	Automatic_Mode	Device is controlled automatically, according to a schedule
Mode_Of_Control	Dynamic_Mode	Device is controlled by a dynamic process, e.g., via a grid signal

4.1. Data coverage

The ASHRAE Global Occupant Database covers a wide range of occupant behavior types, including presence and count of occupant, as well as human building interactions with devices, equipment, and systems in buildings. Those occupant behavior types were categorized into door status, fan status, window status, shading status, lighting status, occupant number, occupancy, appliance usage, and HVAC measurement. This database is designed to support occupant behavior research that informs design and operation of low or net-zero energy buildings. Two case studies are implemented and shown below.

4.1.1. Dataset 1

This dataset was collected in a single occupant office of an educational building in Rende, Italy. The data collection period is from May 2016 to May 2017. Data resolution is one minute. The dataset includes six types of occupant behavior data and six types of indoor and outdoor environmental parameters. In addition, the dataset developer also provided us with the demographic information of the office [41].

For the measured occupant data, the IFC schema is capable of representing data points related to building design elements, such as occupancy, appliance usage, zone information, as well as indoor condition measurements (e.g., temperature, air pressure). While under the Brick ontology, occupancy and thermostat adjustment are covered by the original Brick schema; Appliance usage, window open/close, and door

[3] https://github.com/gtfierro/brick-occupancy-extension
[4] ASHRAE Global Occupant Behavior Database. https://ashraeobdatabase.com

open/close can be further covered by the extended Brick schema. Meanwhile, the occupant's meta information can be covered by the occupant class in the extended Brick schema as well (as shown in Table 5).

In summary, 54% of the total data points can be represented by the IFC schema, which was developed for BIM purposes. 69% of the total data points and 40% of the occupant behavior data points can be represented by the original Brick schema (version 1.2), and now 100% of the data points can be represented by the extended Brick schema.

4.1.2. Dataset 2

The second dataset was collected in three offices in an educational building in Shanghai, China. The data collection period is from May 2018 to November 2018. Data were collected when occupants performed certain behavioral actions (event-triggered). The dataset includes three types of occupant behaviors and seven types of indoor and outdoor environmental parameters.

For the measured occupant behavior data, similar to the first dataset, data points related to the building design can be represented by the IFC schema, such as zone information, thermostat adjustment, and indoor condition measurements. These data points are also covered by the original Brick schema, in addition to outdoor environmental measurements; while other data points related to occupant's actions (e.g., window open/close and shading open/close) can be further covered by the extended Brick schema (as shown in Table 6).

In summary, IFC schema only covers 45% of the total data points. While 82% of the total data points can be represented by the original Brick schema, and now 100% of the data can be represented by the extended Brick schema. For measured occupant behavior data, 67% of the data points can be represented by the original Brick schema, and now 100% of the data can be represented by the extended Brick schema.

4.1.3. Data coverage summary

Based on the available datasets from the ASHRAE Global Occupant Database, we first tested all the qualified datasets with the original Brick schema, and then tested the datasets with the extended Brick schema. In this test, datasets 27, 28, and 29 were evaluated together, since those datasets were contributed from the same project. Table 7 provides detailed test results, which show that the extended Brick schema can better represent the occupant behavior datasets. The most significant improvement in data coverage was 50% for one dataset, and an average of 23% improvement was achieved based on the proposed extended Brick schema. Fig. 6 shows the most improved parameters in different categories. Occupant information was improved the most among other parameters, which confirms the proposed schema's validity.

Table 7 also shows that the extended Brick schema cannot fully (100%) represent some datasets, and those datasets are all Survey type of data. This is because the survey questionnaire and data collection approach are highly varied among different researchers and studies. Moreover, the proposed Brick schema is for general occupant behavior datasets, so it cannot fully cover some unique datasets that were arbitrarily designed/defined by the researcher. For example, in dataset # 1, the author collected some unique data from the participants. Those data included area of window opening, opening-to-wall ratio, area of exterior door openings, total number of window adjustments, reason for adjustment, and other considerations. Table 7 provides the sample data points not covered by the extended Brick.

Table 5
Coverage of occupant data points by the original (version 1.2) and extended Brick schema for dataset 1.

Parameters in dataset	Represented by BIM (IFC schema)	Represented by the original Brick	Represented by the extended Brick
Occupancy	✓	✓	✓
Number of Occupant	✓	✓	✓
Appliance Usage	✓		✓
Window Open/Close			✓
Door Open/Close			✓
Thermostat Adjustment	✓	✓	✓
Indoor Air Pressure	✓	✓	✓
Indoor CO_2 level		✓	✓
Indoor Temperature	✓	✓	✓
Indoor Relative Humidity	✓	✓	✓
Indoor VOC Level		✓	✓
Zone Information	✓		✓
Occupant Information			✓

Table 6
Coverage of occupant data points by the original (version 1.2) and extended Brick schema for dataset 2.

Parameter in dataset	Represented by BIM (IFC schema)	Represented by the original Brick	Represented by the extended Brick
Shading Open/Close			✓
Window Open/Close			✓
Thermostat Adjustment	✓	✓	✓
Indoor Temperature	✓	✓	✓
Indoor Relative Humidity	✓	✓	✓
Indoor CO_2 Level		✓	✓
Indoor Illuminance	✓	✓	✓
Outdoor Temperature		✓	✓
Outdoor Relative Humidity		✓	✓
Solar Irradiance		✓	✓
Zone information	✓		✓

4.2. Brick model of one dataset

4.2.1. Description of the dataset

Building 59 (as shown in Fig. 7) is a medium-sized office building located on the main campus of Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. The building has 10,400 square meters (m^2) of conditioned spaces over four floors. The lower level provides space for mechanical systems, the second level is the NERSC data and computing center, and the third and fourth levels are office spaces. The ground office floor (third floor) is primarily closed office space, while the second office floor (fourth floor) is primarily open office space. The two office floors are served by four rooftop units (RTUs) and underfloor air distribution systems.

The Building 59 dataset contains 337 data points, covering energy use data, outdoor and indoor environmental data, HVAC operational data, and occupant data. Data were collected from various sources and systems, as shown in Fig. 8. All the time-series data streams are pulled from their sources and systems and integrated into an InfluxDB[5] database.

[5] Act in Time. Build on InfluxDB. https://www.influxdata.com/

Table 7
Comparison of data coverage between extended and original Brick schema.

Dataset #	Represented by the original Brick	Represented by the extended Brick	Improvement	Type of dataset	Sample data points not covered by the extended Brick
1	31%	36%	5%	Survey	OccupantDensity; TotalOpenArea
2	100%	100%	0%	In-Stu	–
3	28%	46%	18%	Survey	PredictedMeanVote; ChangePosture
4	100%	100%	0%	In-Stu	–
5	100%	100%	0%	In-Stu	–
6	83%	100%	17%	In-Stu	–
7	94%	100%	6%	In-Stu	–
8	89%	100%	11%	In-Stu	–
9	50%	100%	50%	In-Stu	–
10	75%	100%	25%	In-Stu	–
11	100%	100%	0%	In-Stu	–
12	60%	100%	40%	Survey	–
13	83%	100%	17%	Survey	–
14	83%	100%	17%	In-Stu	–
15	60%	100%	40%	In-Stu	–
16	75%	100%	25%	In-Stu	–
17	67%	100%	33%	In-Stu	–
18	87%	100%	13%	In-Stu	–
19	25%	33%	8%	Survey	ThermalSensation; SleepinessLevel
20	75%	100%	25%	In-Stu	–
21	67%	100%	33%	In-Stu	–
22	60%	100%	40%	In-Stu	–
23	75%	100%	25%	In-Stu	–
24	63%	100%	37%	In-Stu	–
25	65%	100%	35%	Survey	–
26	71%	100%	29%	Survey	–
27, 28, 29	71%	85%	14%	Survey	HousingAssessment; HealthyEatingAssessment
30	57%	100%	43%	In-Stu	–
31	75%	100%	25%	Survey	–
32	67%	100%	33%	In-Stu	–
33	75%	100%	25%	In-Stu	–
34	63%	100%	38%	Survey	–
Average:	**71%**	**94%**	**23%**		

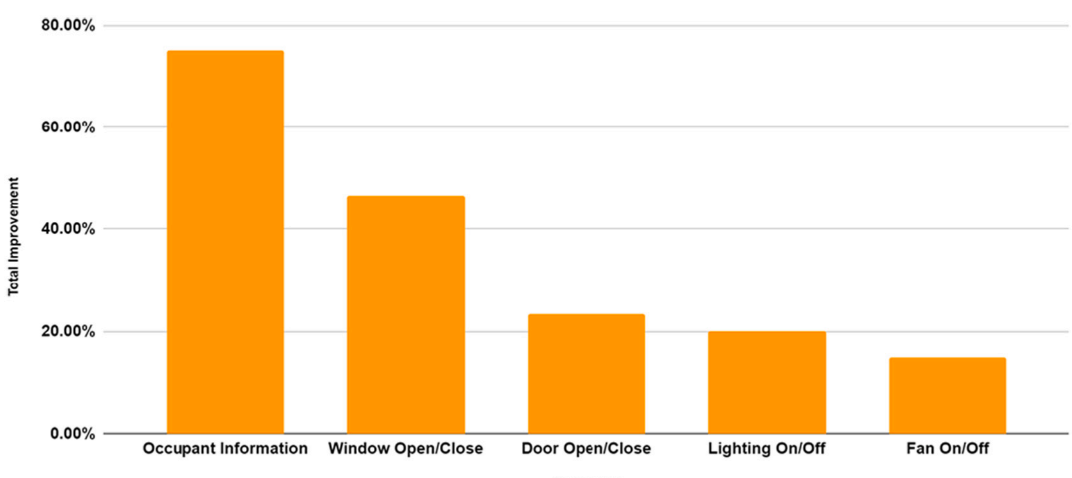

Fig. 6. Most improved occupant-related parameters using the extended Brick schema.

There are two types of occupant-related data collected in the building. First are the occupant count data collected from camera-based sensors, which are available for download from the manufacturer's Traf-Sys system. Second are the Wi-Fi connected device count data collected from the building's IT system.

4.2.2. *Brick model*

We create a Brick model of the Building 59 dataset, using the extended Brick schema. The detailed Brick model is stored in the TTL format and visualized using the tool of Brick TTL Viewer.[6] As shown in Fig. 9, each entity has multiple instances with other entities. For example, the *zone* entity has a relationship with the *VAV* entity under the relationship of *feeds*. it also has relationships with indoor environmental sensors (e.g., *Zone_Air_Temperature_Sensor*, *CO2_Sensor*) under the relationship of *hasPoint*. More specifically, occupant-related data points, such as occupant count and Wi-Fi access points, can be represented using the extended Brick schema.

[6] Brick TTL Viewer. https://viewer.brickschema.org

Fig. 7. Building 59 at LBNL, Berkeley, California.

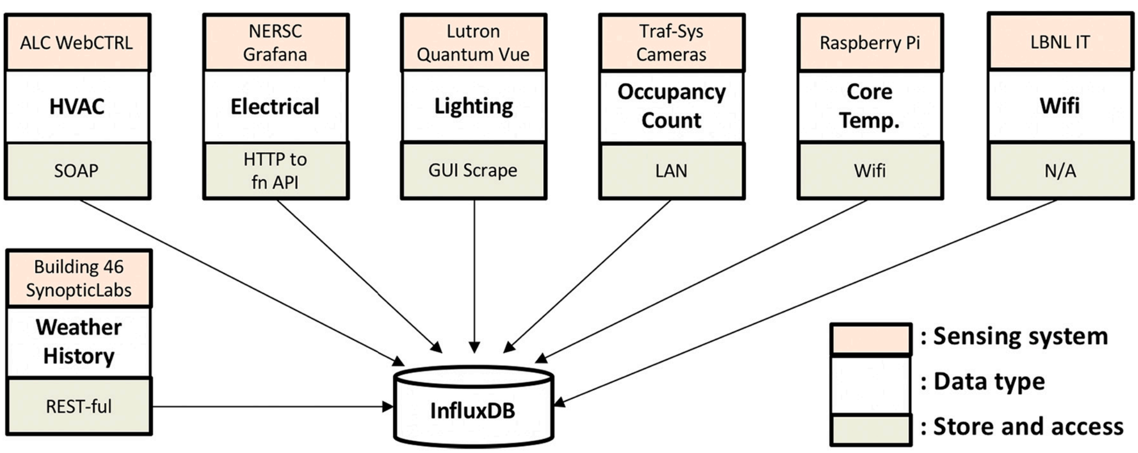

Fig. 8. Data measurements and collection systems.

5. Conclusions

An extension to the Brick schema was proposed and implemented to represent metadata of occupants and their monitored data. The extension includes a new occupant class, several new equipment subclasses, several new point subclasses, and several new entity properties that cover essential meta information of occupants and their monitored data. The ASHRAE Global Occupant Database is used to test the applicability and coverage of the Brick extension, which shows significant improvements in the coverage of occupant data. A sample building dataset was used to test the extended Brick schema. The extended Brick schema enables its use for occupant-centric monitoring, data-driven analysis of the building dataset with occupant data, occupancy-responsive model predictive controls, and occupant-centric building design and operations.

There are limitations to the current implementation, specifically in regards to links between the extended Brick schema and the actual occupancy data. Brick v1.2 supports linking *Point* classes to external data sources such as BACnet objects or time series databases, where there is more structure for accessing and retrieving telemetry in a standard way. In contrast, methodologies and organizations for surveyed data are much more varied and unstructured. This means that it is difficult to model the relationship between *Points* in the Brick model (representing data sources) and the data itself. Future work should address this gap by developing integrations between Brick and formats for storing occupancy data such as obXML. Another limitation is the inevitable lack of comprehensive lists of all possible devices and enumerated property values. Care has been taken to cover common devices, equipment, and property values, and to do so in a structure that can be gracefully extended to account for new types in the future. This approach aligns with the open-source nature of Brick; a growing community steadily adds and refines Brick to include necessary definitions.

The extension will be rolled into the official Brick schema in 2022 and it may be refined to be consistent with other Brick features under

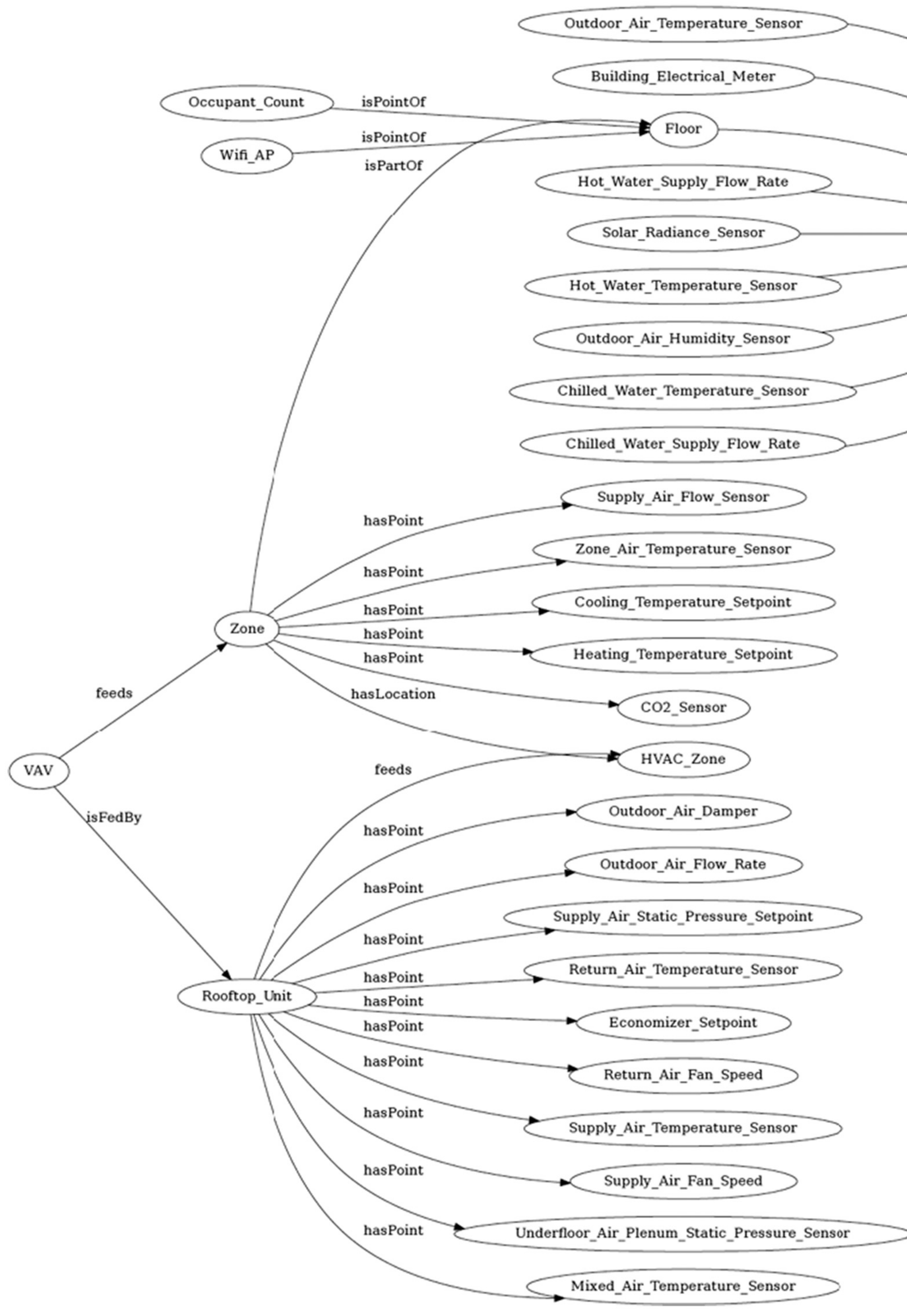

Fig. 9. Class graph of the Brick model for the Building 59 dataset. The diagram shows how instances of Brick classes (represented by nodes) relate to one another.

development, as well as improvements to ensure compliance with the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles.

Declaration of Competing Interest

None.

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