Internet of Things Enabled Data Acquisition Framework for Smart Building Applications

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Abstract: With the networks of sophisticated sensors and devices, building systems have the potential to serve as the infrastructure that provides essential data for the Internet of Things (IoT)-enabled smart city paradigm. However, current building systems lack intersystem connectivity or exposure to the more extensive networks of IoT devices. In this paper, the authors propose an IoT-enabled data acquisition framework that utilizes low-cost computers, sensors modules, developed software agents, and the existing building Wi-Fi network to establish a central facility database. A system prototype is developed for collecting and integrating facility data, and a case study on a university campus is conducted to demonstrate the proposed framework. The potential use cases enabled by the central facility database, the integration of building information modeling (BIM) standards and building system data protocols, a vision for future smart cities, and the challenges are also discussed. This research concludes that the proposed framework is effective in using IoT devices and networks to establish a cost-effective, platform-neutral, scalable, and portable building data acquisition system for smart building innovations. **DOI: 10.1061/(ASCE)CO.1943-7862.0001983.** *© 2020 American Society of Civil Engineers.*

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Introduction

According to the United Nations, the world's urban population is projected to grow by 2.5 billion from 2014 to 2050, when it will account for 66% of the total global population (UN DESA 2015). The growing population in cities increases the demand for the fundamental needs of the people living there, such as housing, utilities, medical care, welfare, education, and employment (Tascikaraoglu 2018). To deal with challenges faced during the growth of cities, the concept of the smart city has been envisioned, which denotes "the effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" (ISO 2014). As the cells of smart cities, smart buildings integrate intelligence, enterprise, control, materials, and construction to advance the building's energy efficiency, longevity, comfort, and satisfaction (Buckman et al. 2014). In both the smart cities and smart buildings contexts, the "smart" refers to the development, integration, and utilization of intelligent systems based on Information and Communication Technologies (ICT).

Smart building applications normally require extensive resources, and their benefits for both private and institutional owners are manifold and often confirmed (Shaikh et al. 2014; Stojkoska and Trivodaliev 2017). How to create intelligent systems for smart building applications has been extensively studied (Ghaffarianhoseini et al. 2018a; Dong et al. 2019), but many challenges still exist regarding building data insufficiency, including a lack of sufficient metering and accessibility and poor data quality (Gao and Pishdad-Bozorgi 2019b; Gao et al. 2019a). In modern buildings, multiple building systems, such as the building automation system (BAS), the building energy system (BEMS), the computerized maintenance management system (CMMS), and the security systems, are collecting a large amount of data through sophisticated sensors and emerging smart devices. However, the systems that generate these data are established based on various data standards and protocols. Thus, the data are not connected or available to analysts and developers in a consumable way (Gao et al. 2018). The lack of comprehensive usage of these building data is hindering innovative applications of smart buildings.

Buildings have both direct and indirect impacts on occupant health, comfort, and productivity (Tham 2016; Mujan et al. 2019). Understanding the indoor environment is critical for research and practices related to improving occupant health. However, the data generated by the current building systems are proprietary, single-purpose, and in various forms that are difficult to integrate and be used for scientific research and innovations. A method to establish an integrated, comprehensive, and real-time building database is needed.

Recent advancements in the Internet of Things (IoT) field provide new opportunities for addressing these challenges related to building data availability. IoT envisions a future in which digital and physical entities can be linked through embedded identification, sensing, and actuation capabilities to enable various innovative

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applications and services that improve the quality of human life. The built environment is a critical component of the overall IoT network (Gao et al. 2019b). Smart home applications are examples of the new functions in the built environment enabled by IoT technologies (Amazon 2019; Google 2019). Research on how to improve data availability, accessibility, and quality in the building sector through IoT technologies is much needed (Gao et al. 2019a).

The research question this study aims to answer is: how to utilize IoT technologies to address the data insufficiency challenge for smart building research and applications. The authors' hypothesis is that the evolving building systems already contain many valuable data for smart building innovations; an IoT-enabled data acquisition framework, which provides integrated and comprehensive building data by generating indoor environment data through sensors and connecting multiple building system databases, can be developed to establish the data foundation for innovative smart building use cases. This IoT-enabled data foundation can be established by (1) using distributed data agents (based on low-cost computers) to extract relevant data from multiple building systems, (2) processing and storing the data in the local databases of the data agents, and (3) integrating the heterogeneous data by connecting the distributed databases via IoT networks.

The research goals are to (1) propose an IoT-enabled data acquisition framework to establish a central facility database that is cost-effective, platform-neutral, scalable, and portable, (2) use the proposed framework to develop a system prototype for collecting and integrating building data, and (3) implement and evaluate the prototype in a case study.

In this study, the developed data acquisition system utilizes low-cost computers, sensors modules, developed software agents, and the existing building Wi-Fi network. This study has the following three major parts: the distributed data agent for extracting data from building systems, the distributed data agent integrated with sensors for indoor environment data generation, and the central database server. To demonstrate the proposed framework, this paper presents a case study using the developed system prototype to establish a comprehensive facility database. The potential use cases enabled by the central facility database are discussed. In addition, the integration of building information modeling (BIM) and can be as high as standards and building system data protocols—a vision for future smart cities—and the challenges are also discussed.

Background

The evolving building systems, such as CMMS, BAS, and BEMS, have the potential to serve as the infrastructure that provides essential data for smart building innovations (Gao et al. 2018). However, partly because of the data availability and interoperability issues discussed in Gao and Pishdad-Bozorgi (2019b), data frameworks that can provide integrated and comprehensive building data for smart building applications are yet to be developed. Extensive studies on the facility information logistics—the right information, at the right time, at the right place, and in the right form—are needed to generate associated real-time data by connecting multiple facility databases and, thus, to enable advanced data analytics for advancing smart built environments (Gao and Pishdad-Bozorgi 2019b).

Building Systems

Each building system is designed to provide specific functionalities for facilities management and control but, with the advancement of ICT, the vendors of modern building systems are expanding their products' functionalities. Thus, there may be some overlaps among them. For example, some BAS may have certain energy management functions (Ehlers et al. 1996). Regardless of the existing and potential overlaps, mainstream building systems are summarized as follows.

Building Automation System (BAS). The BAS is also known as the building management system (BMS). The BAS is a computer-based system that monitors and controls the building's mechanical and electrical equipment, such as heating, ventilation, air-conditioning (HVAC) systems, fire systems, and security systems (Donnell et al. 2010; Figueiredo and Martins 2010). A BAS uses sensors to collect data on the building's conditions and uses actuators to conduct physical control. A large number of records on temperature, power, flow rate and pressure, control signals, states of equipment, and others are collected by the BAS and stored in its database (Xiao and Fan 2014).

Building Energy Management System (BEMS). A BEMS is a comprehensive approach to monitor and control the building's energy needs by collecting the building's energy-related data, analyzing the performance status, and controlling corresponding equipment (ClimateTechWiki 2019). Similar to the BAS, the BEMS is generally applied to the control of active systems, such as the HVAC and lighting systems. The main difference between a BEMS and other building systems is the characteristic of energy-related data collection, processing, and centralized and automated building control (IEA 1997). The role of the BEMS is known and significant because BEMS can contribute to continuous energy management and, thus, to achieve energy and cost savings and building occupants' comfort (Doukas et al. 2007). When the goal of energy saving is expanded to reducing environmental impacts, the name environmental management system (EMS) is used instead of BEMS.

Computerized Maintenance Management Information System (CMMS). The CMMS, also known as the computerized maintenance management information system (CMMIS), is utilized by facilities maintenance organizations to record, manage, and communicate their daily operations (Sapp 2013). The core function of a CMMS is "to manage information related to maintenance, including but not limited to work orders, asset histories, parts inventories, maintenance personnel management and the calculation of maintenance metrics" (Lewis et al. 2010). The CMMS is an essential tool for modern facility operation and maintenance work because it can (1) provide building component information for maintenance and repair work, (2) generate reports for managing resources, (3) prepare facilities' key performance indicator (KPIs) metrics for evaluating the effectiveness of the current operations, and (4) support organizational decision making (Sapp 2013).

Indoor Environment Sensing

Some noteworthy progress has been made in the smart building paradigm during the past decade, especially in its applications with the development of sensing systems. Studies related to the field of built-environment sensing aim to investigate the type of data that can be collected and monitored through sensing devices. They deal with the implementation of these data toward application areas, such as health-hazard detection and mitigation, meeting sustainability standards, optimum energy consumption, and thermal conditions. A study conducted by Teixeira et al. (2010) envisioned the use of sensor devices for detecting occupants' presence, number, location, and activity in an indoor setting. Subsequently, many research studies have been conducted by utilizing sensing technologies for detecting and monitoring occupant activities with the aim to provide energy-efficient, smart, sustainable buildings (Jazizadeh et al. 2012; Zou et al. 2018; Jia et al. 2019). In parallel, researchers have also been able to identify the influence of indoor environmental conditions on occupant health and comfort in terms of indoor air quality, acoustic comfort, visual and lighting conditions, vibrational disturbances, and odor and thermal conditions (Tham 2016; Ghaffarianhoseini et al. 2018b; Andargie et al. 2019). These efforts have enabled researchers to shift their focus toward human-sensing in indoor environments for improved occupant health and effective human-building interaction by incorporating sensing systems to monitor indoor environmental conditions. However, challenges such as the cost effectiveness of sensing devices may hamper its adoption in the built environment, especially when taking affordable housing into consideration (Dong et al. 2019). In addition, transmitting collected information containing sensor readings and occupant profiles to facility managers in real time can be a critical gap that needs to be adequately addressed.

IoT-Enabled Data Acquisition in the Built Environment

In built environments, the viability of automated sensing systems is determined by its resilience toward the dynamic changes of indoor environmental conditions. The emergence of IoT technology has paved the way for a new paradigm focused on developing smart gadgets for sensing, identifying, and communicating capabilities within various semiautomated and manual facility systems (Verma et al. 2019).

Existing research studies demonstrate the use of IoT devices based on their purpose and application. The selection of sensors depends on, but is not limited to, gathering information of the respective parameter for which the sensor is originally deployed. For instance, to monitor indoor air quality, air velocity sensors, volatile organic compounds, and particulate matter sensors, as well as sensors capable of computing CO_2 and other gaseous concentrations, are used (Kumar et al. 2016; Saha et al. 2018; Zakaria et al. 2018). To better understand the influence of thermal conditions in the indoor environment, temperature and humidity sensors are widely used (Coleman et al. 2017; Tran et al. 2017). Moreover, lighting conditions and visual comfort are regulated by deploying photometric sensors because of their ability to control luminaire intensity (Dong et al. 2019; Chinazzo et al. 2020). Acoustic discomfort and vibrational disturbances are evaluated by utilizing sound pressure sensors and accelerometers due to their ability to measure pressure wave and vibration intensities (Fernandes et al. 2017; Risojević et al. 2018; Andargie et al. 2019).

Issues of Current Data Solutions

Current industrial solutions for capturing the data related to the indoor environment and building systems have multiple shortcomings that hinder them from being widely implemented in existing buildings. Some of the major issues are stated here.

Cost. The high cost of the comprehensive commercial solution is the main reason building owners are reluctant to install advanced building systems in their buildings (Rawal 2016). The cost to deploy a basic building management system is at least \$26.9 per m^2 (\$2.50 per ft^2) and can be as high as \$75.3 per m^2 (\$7.00 per ft^2) (NRECA 2020). The high cost of the commercial data solution makes the return on investment (ROI) a challenge for all but the largest buildings (Rawal 2016).

Data Proprietary. Buildings systems, such as energy systems, security systems, and emerging smart home systems, already incorporate proprietary networks of sophisticated sensors and devices, but their intersystem connectivity is limited. The data generated and collected by one system can seldom be used directly by another. Using the data housed in separate systems to create a central facility repository has always been challenging (Gao and Pishdad-Bozorgi 2019b).

Scalability. For many building systems, as soon as the initial installation is completed (typically during or right after the construction of the building), it is challenging to expand the system by adding more devices or deploying a subsystem. Therefore, when a building space's functions change, making changes to the building's existing systems to acquire more data might be difficult or even impossible.

Portability. Most building systems installed during construction cannot be subsequently ported to a different location, or the cost of moving them is higher than the cost of installing new ones. This issue makes it difficult to adapt existing systems to meet the needs for future changes in building space functions.

Research Method

To address the cost, data proprietary, scalability, and portability issues in existing building data systems, the authors first propose an IoT-enabled data acquisition framework that enables the utilization of the data generated by low-cost sensors and housed in separate building systems. To examine the usability of the proposed data acquisition framework, the authors then designed and built a proto type system that consists of several minicomputers—Raspberry Pi 4 Model B (Broadcom, San Jose, California), multiple sensor modules, and developed databases (MariaDB version 10.4) and software agents (Python version 3.7.2 scripts). This cost-effective, comprehensive, scalable, and portable data system can (1) automatically acquire data from a given building system that publishes data on a website, (2) generate indoor environment data, such as temperature, humidity, movement detection records, illumination, sound, and others, and (3) integrate the acquired and generated data and store the data in a central database server.

A proof-of-concept case study was conducted to demonstrate the developed system prototype. A comprehensive facility database was established by integrating the indoor environment data generated by the data agents deployed in a campus building and the data acquired from a public building's websites. Four potential use cases of the established central facility database are then discussed.

Data Acquisition Framework for Smart Built Environment

This section introduces a conceptual framework for utilizing IoT to acquire facility-related data and, thus, establish a central facility database for smart building innovations. This framework aims to establish a cost-effective, comprehensive, scalable, and portable IoT infrastructure for indoor environment data generation, collection, integration, and presentation. Fig. 1 illustrates the high-level concept of establishing the data foundation by deploying the sensor network, extracting data from building systems, and storing data in a central database.

In the proposed framework, the data generated in each building system are collected periodically using dedicated data adapters (#$1, 2, 3, \ldots, n$) and stored in the databases housed in distributed data agents (#$1, 2, 3, \ldots, n$). These data agents can also be integrated with multiple sensors that generate indoor environment data (such as temperature, humidity, vibration, illumination, and people counting), which are also stored in the local database of the agent (#$n+1, n+2, \ldots$). Connected through a wireless network, such as the Wi-Fi in a building, the data agents provide data streams to the data adapters ($A, B, \ldots, M$) operating on the central server. Hence, the facility data generated from different sources are saved in the central database server in real-time.

The data agents are low-cost and energy-efficient minicomputers with data adapters (software agents) running 24 h a day, seven days a week. The data adapters extract data from building

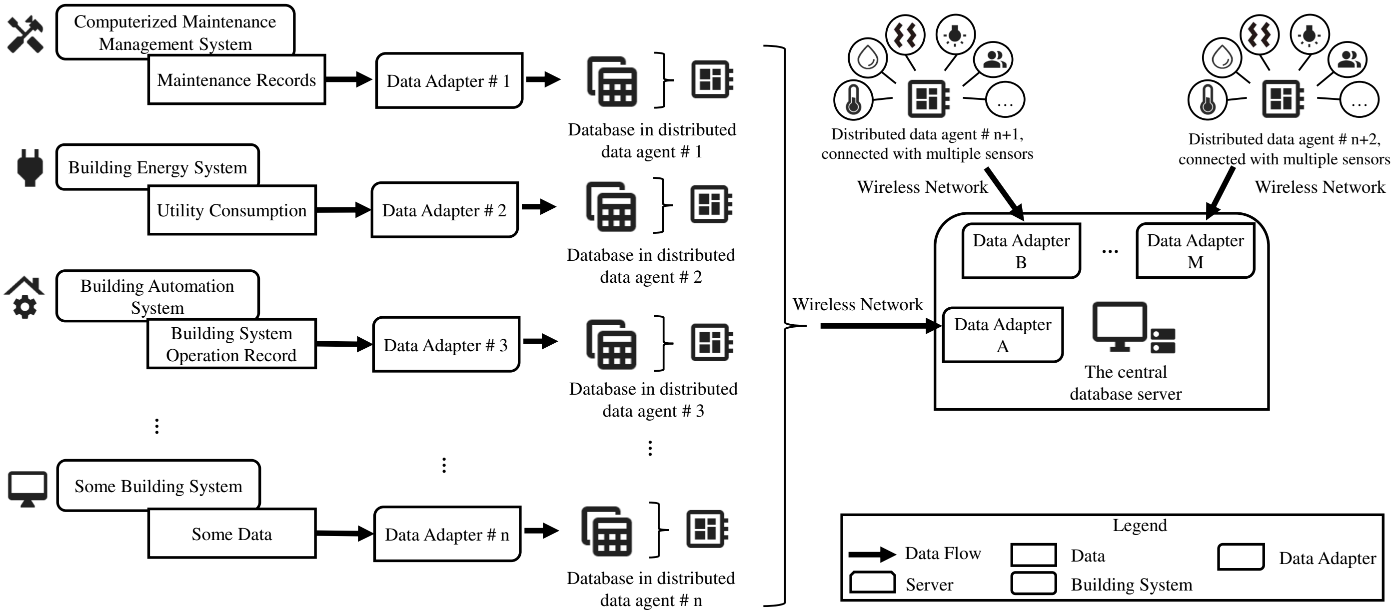


Fig. 1. Data acquisition framework for smart built environment. [Icons courtesy of Material.io, licensed under the Apache License, Version 2.0 (http://www.apache.org/licenses/LICENSE-2.0).]

systems, save the data in the local database, collect data generated by connected sensors, and push the data stream to the data adapters running on the central data server. An example of the data agent integrated with multiple sensors is provided in Fig. 2. This data agent is built based on the minicomputer Raspberry Pi and integrated with temperature and humidity, vibration, illumination, and sound sensors.

Fig. 3 illustrates the conceptual model of the data adapter for acquiring data from different building systems (data adapter #1, 2, . . . , *n* in Fig. 1). Different types of data adapters exist based on different data availability scenarios. When direct access (backend login with username and passwords) to the building system's database is available, the data adapter can be a software agent (bot) that accesses the database and reads the data periodically. When no direct access is available, but the system software program provides an application programming interface (API), the data adapter can be a software agent that extracts data using the API. If no direct access or API is available, but the building system's data are published on a webpage, the data adapter can be a web scraper for extracting data from the webpage. If the building system manager does not provide any access but is willing to perform a regular data dump, the data adapter can be a webpage for the manager to upload the data. When acquiring the data, the data adapter also cleans and formats the data and then writes the data

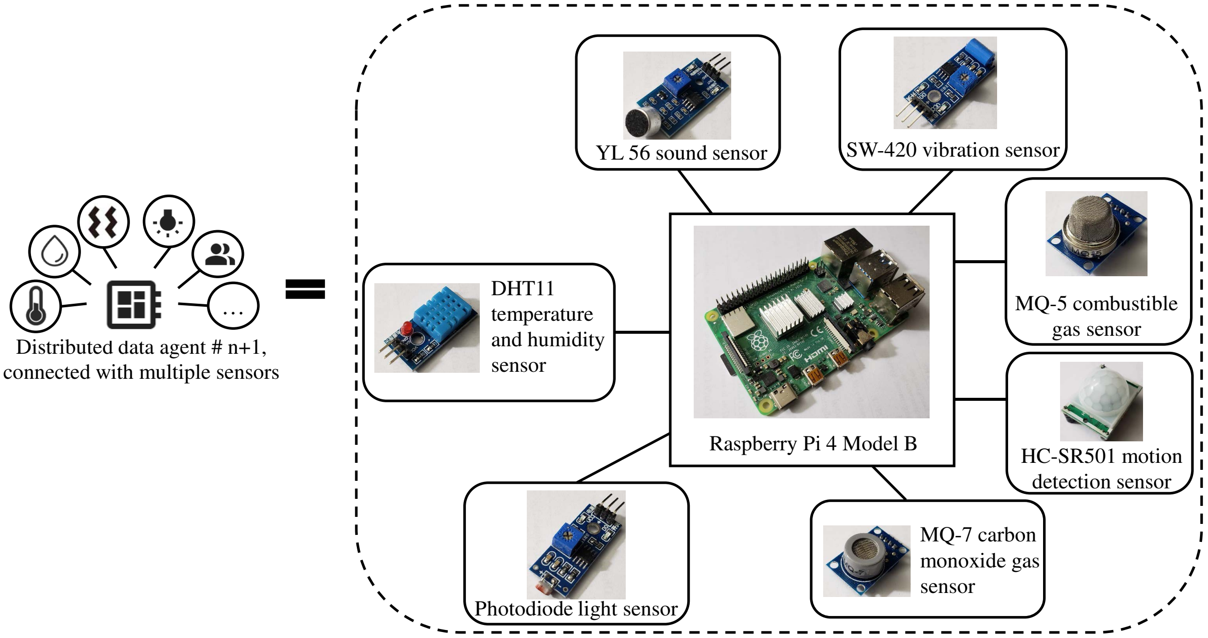


Fig. 2. Example of data agent integrated with sensors. [Images by authors; icons courtesy of Material.io, licensed under the Apache License, Version 2.0 (http://www.apache.org/licenses/LICENSE-2.0).]

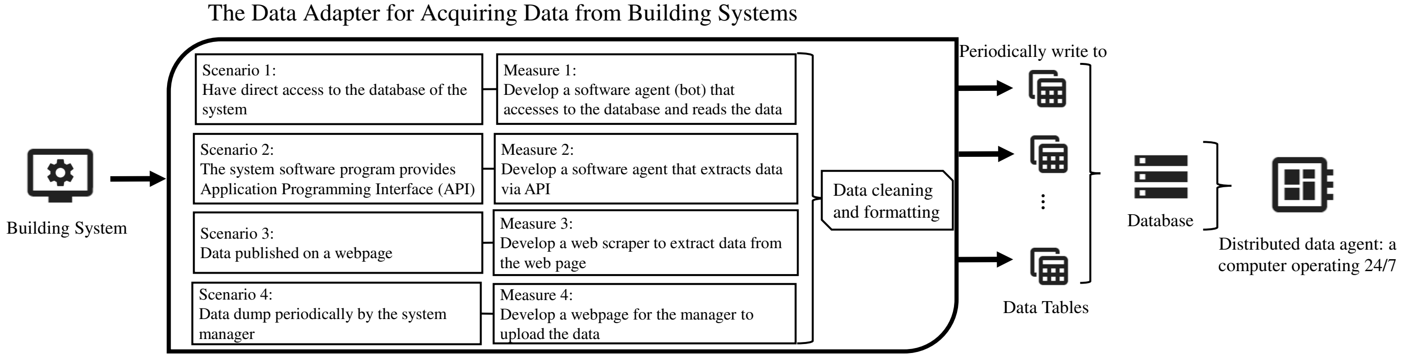


Fig. 3. Data adapter for acquiring data from building systems. [Icons courtesy of Material.io, licensed under the Apache License, Version 2.0 (http://www.apache.org/licenses/LICENSE-2.0).]

to the corresponding data tables in the database of the distributed data agent.

The central database server houses comprehensive real-time facility data and provides database services to facility-related software programs. The data adapters running on the central database server (data adapter $A, B, \ldots, M$ in Fig. 1) serve as bridges between the databases housed in distributed data agents and the central database server. They continuously retrieve data streams from the former and save to the latter.

Prototype of Facility Data Acquisition System

To demonstrate the proposed framework, the authors developed a system prototype for collecting and integrating facility data, as indicated in Fig. 4. This system consists of three major parts: the distributed data agent for extracting data from building systems, the distributed data agent integrated with sensors for indoor environment data generation, and the central database server.

Data Agent for Extracting Data from Building Systems

The authors used Raspberry Pi 4 Model B as the hardware platform for the data agent. Raspberry Pi is a series of small, low-cost, and energy-efficient single-board computers. A Raspberry Pi 4 Model B [1 gigabyte (GB) random access memory (RAM)] costs about \$35, has a processor, a RAM, expandable storage [mini secure digital (SD) card socket], and a Wi-Fi module, and is compatible with the Linux-based operating system (in this case, Raspbian is used). It is a fully functional computer, and software applications such as database programs, data analysis programs, and software agents can execute on it independently. These features make the Raspberry Pi suitable for serving as the dedicated data agent that acquires data from building systems.

The data agent is designed to acquire the data published by a building system on a limited-access website, as Fig. 4 indicates. When developing the prototype, the authors chose Scenario 3 in the proposed framework (provided in Fig. 3) because it is the most challenging scenario among the four in terms of data adapter development. In Scenario 3, neither database access nor any API is available, and no facility manager is available to provide the data. Typically, facility managers are reluctant to publish building system data to the public because of cybersecurity considerations, but many building systems do have the functionality to publish data on a website, which is usually limited-access and for internal usage only (Gao and Pishdad-Bozorgi 2019b). The data adapter executing on this data agent aims to constantly extract data from such an

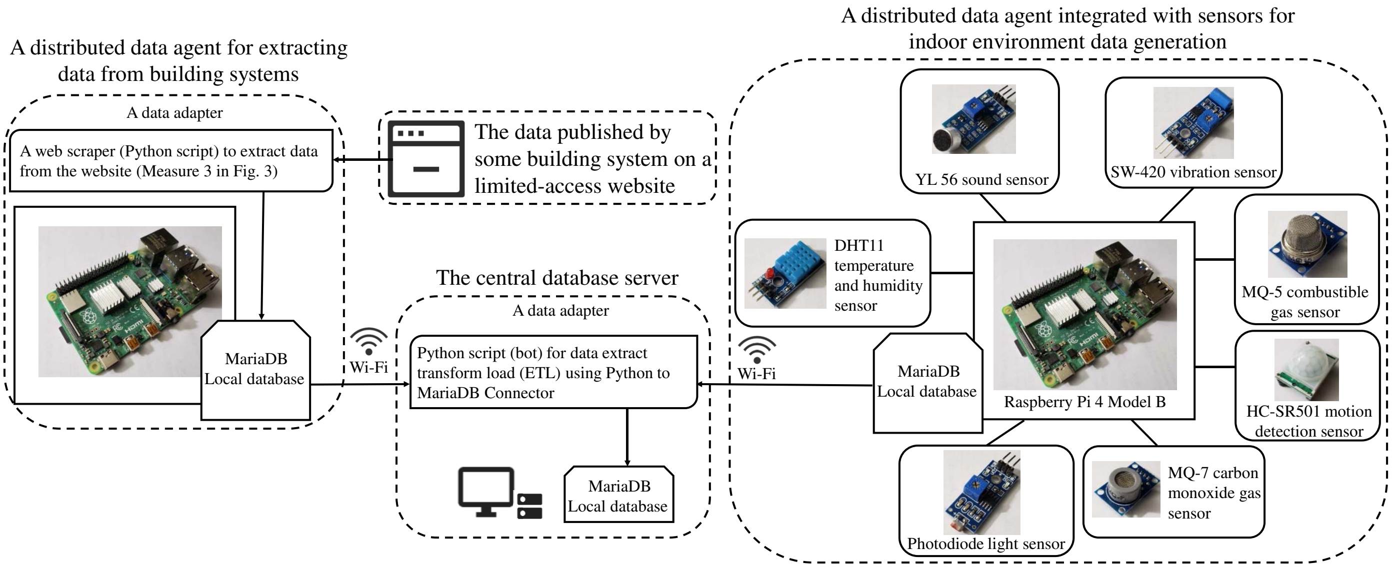


Fig. 4. Prototype of facility data acquisition system. [Images by authors; icons courtesy of Material.io, licensed under the Apache License, Version 2.0 (http://www.apache.org/licenses/LICENSE-2.0).]

internal website and save the data to the local database housed in the data agent. To achieve that aim, the authors developed a web scraper using Python that can read a webpage periodically, download the required data, and save the data to the database (Gao 2019). The Raspberry Pi receives the indoor environment data generated by the sensor modules through the general-purpose input/output (GPIO) ports and is programmed to run in an infinite loop to collect data continuously. A 60-s interval exists between the readings. To synchronize with the sensor data, the web scraper also reads every 60 s. The data agent is programmed to communicate with the central server once every hour. This data adapter also works for a public website.

MariaDB is a free and open-source relational database management system (RDBMS) and is adopted in the developed prototype system as the database program. A Python to MariaDB Connector provides the support for Python to manage the data stored in the MariaDB database. In the developed data agent, the data extracted from the building system by the adapter are stored in the local MariaDB database.

Data Agent Integrated with Sensors for Indoor Environment Data Generation

The distributed data agent used for generating and collecting indoor environment data was developed by connecting sensor modules with a Raspberry Pi via its GPIO. The authors installed seven types of sensors on the data agent, including temperature and humidity, sound, vibration, combustible gas, carbon monoxide, lighting, and motion detection sensors (as Fig. 5 indicates). The system is capable of including more sensors as needed. The following is the list of sensors that we are currently using.

- DHT11 temperature and humidity sensor (AiTrip, Shenzhen, China). This sensor provides temperature and humidity readings. The authors used degrees in centigrade and percentages for the temperature and humidity units, respectively.
- Photodiode light sensor (Dragonmarts, Hong Kong). The light sensor is one of the digital sensors that provides 0 when it detects light and 1 if it does not detect any light. The sensor has a tuning potentiometer (POT) for adjusting the reading threshold.
- YL 56 sound sensor (Anmbest Control Technology, Wuhan, China). The sound sensor is also a digital sensor that detects changes in sound amplitude and provides a high reading. This reading can be called a beat. The number of beats in a minute was counted for the data record.
- SW-420 vibration sensor (HiLetgo Technology, Shenzhen, China). The vibration sensor can detect nearby vibrations and provides a reading. It is a binary sensor, and we also used the counting mechanism with this one.
- HC-SR501 motion detection sensor (FlyFun Technology, Shenzhen, China). The motion sensor records the intensity of the motion detected nearby and comes with a tuning potentiometer.
- MQ-5 combustible gas sensor (Jinkangfa Electric Technology, Shenzhen, China). The MQ5 is an analog sensor that required an additional analog to digital converter circuit for implementation. This sensor can provide continuous readings of H_2, LPG, CH_4, CO, and alcohol.
- MQ-7 carbon monoxide gas sensor (HiLetgo Technology, Shenzhen, China). The MQ-7 is also an analog sensor and requires an additional analog to digital converter circuit to implement. This sensor can provide continuous CO readings.

A Python script is continuously executing on the data agent to save the data generated by the sensors into a MariaDB database (Gao 2019). This data agent only requires a constant power supply of 5.1 V, 3.5 A to the Raspberry Pi; hence, it can be deployed almost at any location in a building.

Database Configuration

The central server in the prototype system is a desktop computer with Windows 10. The computer has a MariaDB serving as the central database and a data adapter that performs extract, transform,

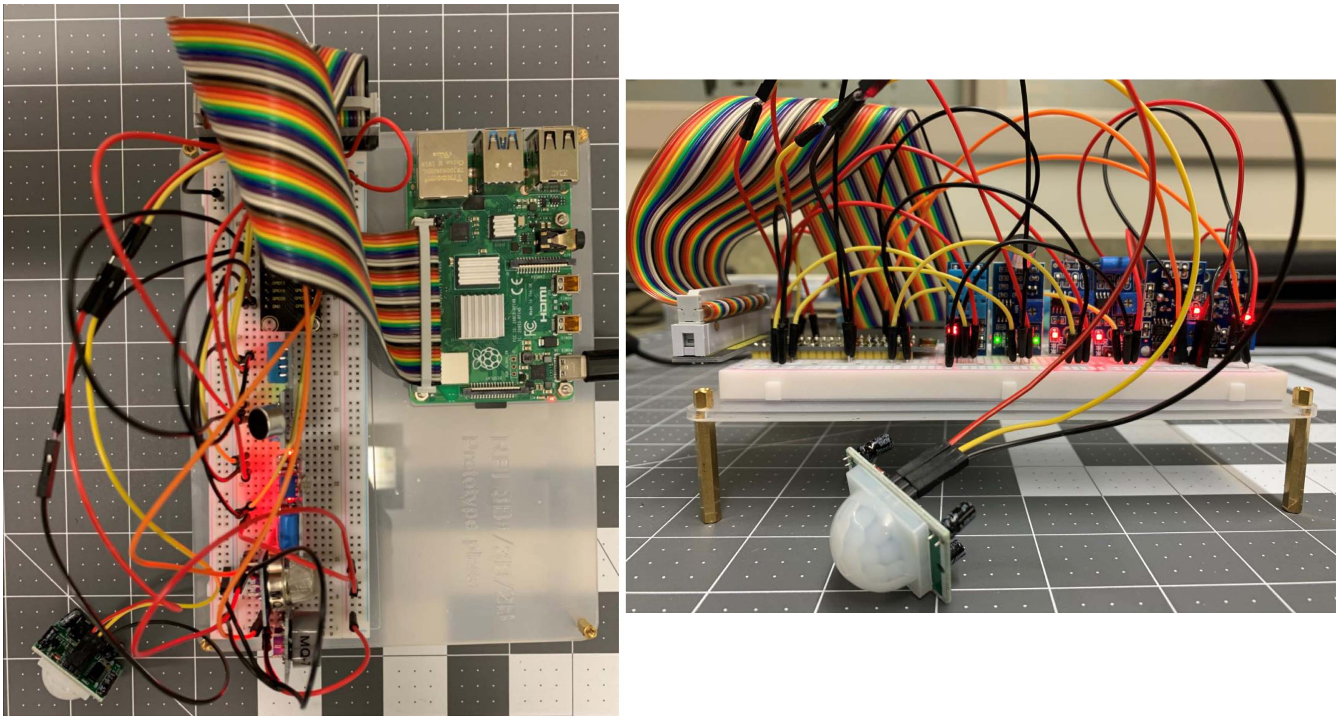


Fig. 5. Data agent integrated with sensors.

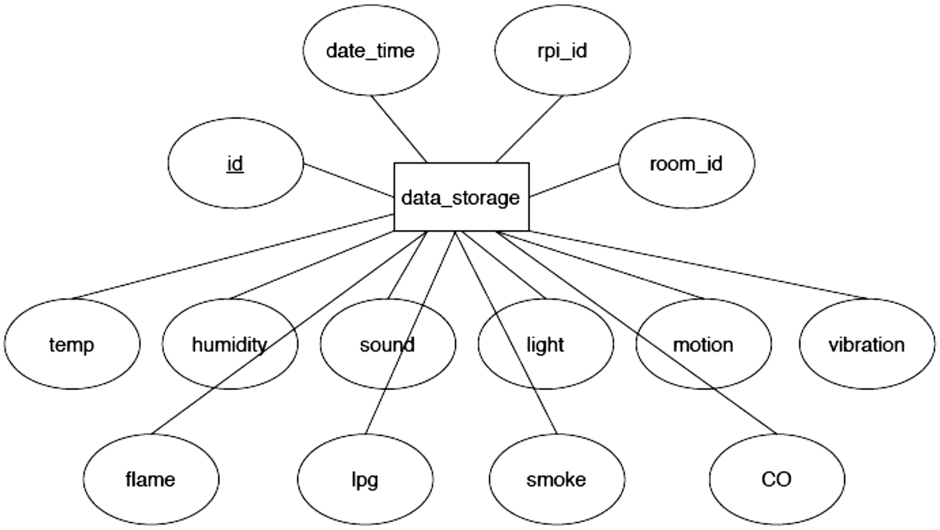


Fig. 6. Database's entity diagram.

and load (ETL) between the distributed data agent's local database and the server's central database. This data adapter is also developed in Python and utilizes the Wi-Fi network to connect to each data agent (Gao 2019).

The developed prototype system consists of low-cost minicomputers, free database programs, customized software agents (Python scripts), and the Wi-Fi network, and can establish a central database that stores real-time, comprehensive facility data by extracting data generated by building systems and sensing the indoor environment.

The developed system has two separate database designs. One design is used in the data agents and another in the central server. Fig. 6 indicates the entity diagram of the database collecting the data rows. This table is the same in both database designs. Each record is denoted by a unique id generated from the combination of date_time, rpi_id (Raspberry Pi ID), and room_id. The date_time, rpi_id, and room_id are string data and present in the table to enable faster queries. The rest of the columns represent different information records related to the sensors, such as light presence, temperature, sound, and others. The central database contains additional tables to keep track of the module placements and sensors.

Proof-of-Concept Case Study

The research team conducted a case study using the developed system prototype to establish a comprehensive facility database. The authors could not find an organization both providing access to its building system's database or internal webpage and allowing the deployment of the data agent with sensors. Hence, the case study is divided into two parts. The first part is evaluating the data agent for extracting data from building systems. The data generated by the building systems of the Net-Zero Energy Residential Test Facility (NZERTF) (NIST Engineering Laboratory 2019b), which are published online, were extracted and stored in the local database housed in the data agent and then pushed to the central database. The second part is evaluating the data agent integrated with sensors for indoor environment data generation. Eight of these data agents were deployed in a campus building and generated data for two weeks. These indoor environment data, together with the NZERTF building system data, were integrated and stored in the central database server.

Acquiring Building System Data from NZERTF

Established by the National Institute of Standards and Technology (NIST), the NZERTF is a two-story, four-bedroom, three-bath, single-family house with zero net energy consumption (NIST Engineering Laboratory 2019b). NZERTF has sensors and instrumentation on multiple facets, from energy consumption to comfort, and the NZERTF data capture diverse high precision measurements (NIST Engineering Laboratory 2019c). There are nearly 400 data channels across 11 subsystems (NIST Engineering Laboratory 2019a).

In this case study, the developed data agent was used to extract a part of NZERTF's data from its website. The data involve (1) the electrical and thermal loads by equipment and people, (2) photovoltaic-related data, such as the temperature of the PV module and AC energy generation, and (3) ventilation-related data, such as flow rate of air in the exhaust duct and pressure differential across the heat recovery ventilator. Because NZERTF only provides the data from July 1, 2013, to January 31, 2016, the "old" data from February 1, 2015, were extracted by the developed web scraper at an interval of 1 min to simulate the process of collecting from a real-time data stream and, thus, to prove the concept of the data adapter. The extracted data were stored in the central database developed.

Indoor Environment Sensing

The four-story campus building, in which the data agents with sensors were deployed, houses administrative and faculty offices and provides classroom space, seminar rooms, and studios (as Fig. 7 indicates). The eight data agents were deployed in a faculty office, a meeting room, two classrooms, a studio, a corridor, and two opening study places, respectively (as Fig. 8 indicates). In public spaces (meeting room, classroom, studio, corridor, and opening study places), the data agents were mounted on the ceiling in the center of the room; in private spaces (offices), the data agents were placed on the table in the center of the room. From November 1, 2019, the indoor environment data were generated, collected, and stored in each agent's local database. These data involve temperature, humidity, sound, vibration, combustible gas, carbon monoxide, lighting, and motion detection. The interval between the readings was set to 1 min. A twofold solution was implemented to solve the data

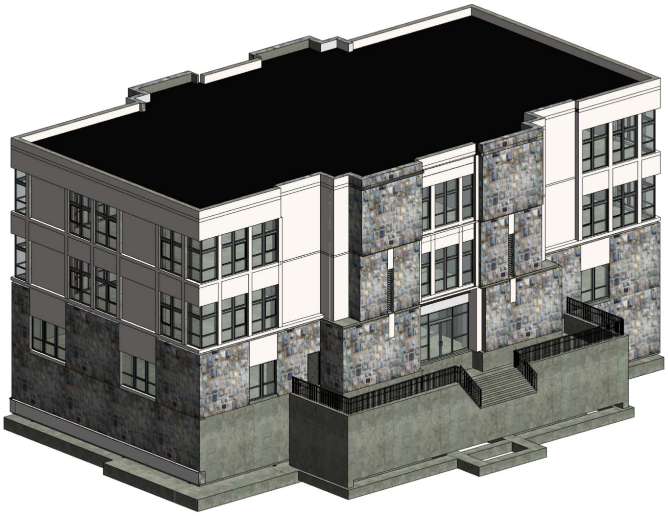


Fig. 7. Campus building studied.

synchronization issue. The authors designed a routine update mechanism between the data agents and the central server. Instead of transferring data records, files consisting of multiple records were transferred. A record checking system was also implemented in the data agent to maintain consistency. The missing data were recorded as *Null* in the database.

Central Facility Database

A central facility database was established on the server, integrating the acquired data from NZERTF and the generated indoor environment data, as Fig. 9 indicates.

Three example data streams from NZERTF are visualized in Fig. 10: (a) the cumulative energy consumption starting at midnight by lights on the first floor, in W · h, (b) instantaneous current produced from the Phase A wire from inverter 1, in A, and (c) instantaneous flow rate of air in the return flow duct entering the heat recovery ventilator, in ft^3/min. The timeframe of these examples is from February 1, 2015, to February 7, 2015.

Three example data streams of the campus building's indoor environment, from the data agent deployed in the faculty office, are visualized in Fig. 11: (a) the temperature, (b) the humidity, and (c) the count of actions detected each hour. The timeframe of these examples is from November 1, 2019, to November 7, 2019.

Cost, Data Proprietary, Scalability, and Portability

The prototype system deployed in the case study is cost-effective. The total cost of the 10 data agents (two for NZERTF data extraction and eight for indoor environment sensing) is approximately \$700. The desktop computer that houses the central database costs approximately \$1,500. There are no other costs because the database solution, MariaDB, and Python programming tool are free, and the system used the building's existing Wi-Fi network.

The system solved the data proprietary issue of the studied building systems. The data extracted from the NZERTF building systems and generated in the studied building are integrated and saved in a single database. The data stream is formatted and is ready to use and share.

The system is scalable and has the option to add or remove data agents, sensor modules, and data to acquire as needed. Making changes in individual data agents will not influence the overall system operation. Moreover, the system is not attached to any building structure or system. Thus, it is portable anytime and anywhere with a power supply and Wi-Fi network.

Use Cases and Future Work

In the case study, a central facility database is established by implementing the prototype system that generates, collects, and

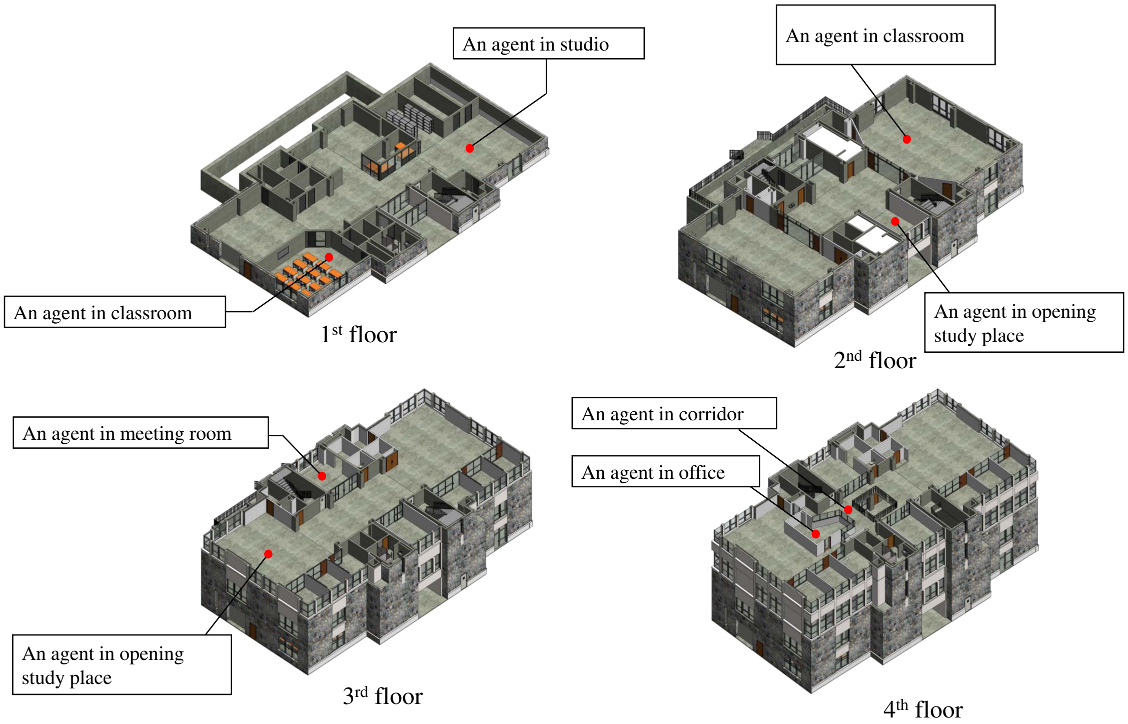
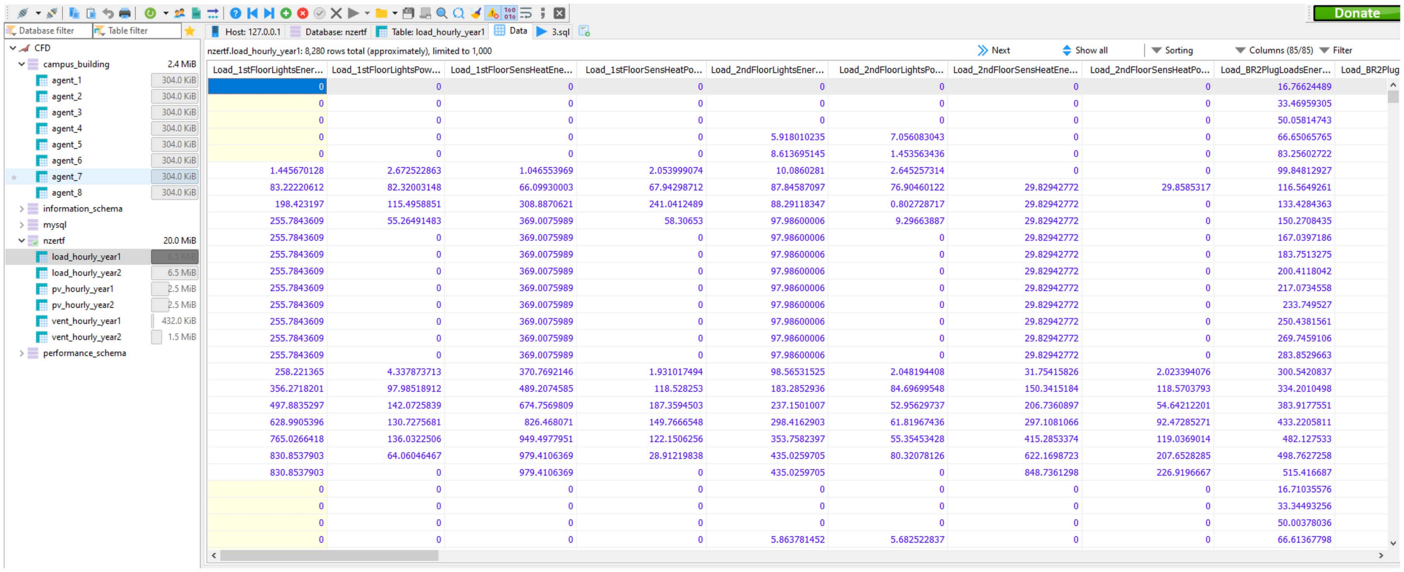


Fig. 8. Deployment of data agents in case study.



nzertf.load_hourly_year1: 8,280 rows total (approximately), limited to 1,000

Load_1stFloorLightsEner...	Load_1stFloorLightsPow...	Load_1stFloorSensHeatEne...	Load_1stFloorSensHeatPo...	Load_2ndFloorLightsEner...	Load_2ndFloorLightsPo...	Load_2ndFloorSensHeatEne...	Load_2ndFloorSensHeatPo...	Load_BR2PlugLoadsEner...	Load_BR2Plug
0	0	0	0	0	0	0	0	16.76624489	
0	0	0	0	0	0	0	0	33.46959305	
0	0	0	0	0	0	0	0	50.05814743	
0	0	0	0	5.918010235	7.056083043	0	0	66.65065765	
0	0	0	0	8.613695145	1.453563436	0	0	83.25602722	
1.445670128	2.672522863	1.046553969	2.053999074	10.0860281	2.645257314	0	0	99.84812927	
83.22220612	82.32003148	66.09930003	67.94298712	87.84587097	76.90460122	29.82942772	29.8585317	116.5649261	
198.423197	115.4958851	308.8870621	241.0412489	88.29118347	0.802728717	29.82942772	0	133.4284363	
255.7843609	55.26491483	369.0075989	58.30653	97.98600006	9.29663887	29.82942772	0	150.2708435	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	167.0397186	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	183.7513275	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	200.4118042	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	217.0734558	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	233.749527	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	250.4381561	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	269.7459106	
255.7843609	0	369.0075989	0	97.98600006	0	29.82942772	0	283.8529663	
258.221365	4.337873713	370.7692146	1.931017494	98.56531525	2.048194408	31.75415826	2.023394076	300.5420837	
356.2718201	97.98518912	489.2074585	118.528253	183.2852936	84.69699548	150.3415184	118.5703793	334.2010498	
497.8835297	142.0725839	674.7569809	187.3594503	237.1501007	52.95629737	206.7360897	54.64212201	383.9177551	
628.9905396	130.7275681	826.468071	149.7666548	298.4162903	61.81967436	297.1081066	92.47285271	433.2205811	
765.0266418	136.0322506	949.4977951	122.1506256	353.7582397	55.35453428	415.2853374	119.0369014	482.127533	
830.8537903	64.06046467	979.4106369	28.91219838	435.0259705	80.32078126	622.1698723	207.6528285	498.7627258	
830.8537903	0	979.4106369	0	435.0259705	0	848.7361298	226.9196667	515.416687	
0	0	0	0	0	0	0	0	16.71035576	
0	0	0	0	0	0	0	0	33.34493256	
0	0	0	0	0	0	0	0	50.00378036	
0	0	0	0	5.863781452	5.682522837	0	0	66.61367798	

Fig. 9. Central facility database.

integrates data from building systems and the deployed data agents. This type of facility database providing the real-time data stream offers the potential for innovations in the smart built environment. This section discusses the potential use cases of the central facility database, the data protocol level integration of building information and building system information, a vision for a future smart city, and the limitations of this research and challenges for IoT-enabled smart building innovations.

Use Cases

Use Case 1: Facility Life-Cycle Cost Analysis with Machine Learning

Advanced data analysis techniques, such as machine learning, have been used for predicting facility life-cycle costs (LCC), but the lack of sufficient facility data is hindering the development of effective LCC prediction tools (Gao et al. 2019a). A central facility database established through the proposed framework provides a solution to the data insufficiency issue. For example, Gao and Pishdad-Bozorgi (2019a) developed machine learning models for facility LCC analysis using the historical data stored in building systems. A central database that incorporates all of the required data from multiple building systems can serve as the data foundation for the development of automated prediction models and tools.

Use Case 2: Improved Energy Modeling and Calibration

A gap always exists between simulated building energy consumption and measurement, and building energy model calibration is a process of tuning the simulation model inputs to minimize the gaps between predicted and actual building energy consumption (Reddy 2006). Calibrating building energy models requires detailed data records. The central database established through the proposed framework provides the data platform for building energy model calibration and enables the process to be streamlined. For example, in a case study conducted by Chen et al. (2019), the research team utilized the historical data extracted from the building energy management system to calibrate the developed energy simulation models.

Use Case 3: Occupant Status Sensing

The indoor environment is critical for occupants' health and well-being, and technologies exist for people's health monitoring, such as wearable sensors, and for indoor environment evaluation (Verma et al. 2019). However, the inherent relations between the two are not well studied because of the difficulties in collecting real-time data from occupants and their ambient environment in the long term. In the proposed data acquisition framework, the data agents distributed in a building can serve as the base station that receives the real-time data sent by wearable sensors mounted on occupants' bodies. With wireless signal receivers installed on the data agents and communicating with the transmitter connected to the wearable sensors, a real-time data foundation can be established in a building to collect data on occupants' status and their ambient environment. This type of data foundation opens opportunities for research studies and innovations, such as patient status monitoring, real-time indoor environment evaluation and hazards detection, and long-term occupant health tracking, among others.

Use Case 4: Data-Driven, Automated Building Control

In recent years, innovative and low-cost smart building and smart home devices are emerging in the consumer market, such as Amazon Alexa and Google Home. The data framework proposed in this study can be incorporated into the maturing smart building paradigm. A series of software applications can be developed based on the central facility database to perform data analysis for automated building control. For example, by learning from the historical data, such as the outdoor temperature, indoor temperature, and occupants' thermal preference, an intelligent system can predict trends in the optimal thermostat settings. Furthermore, with software agents running, the distributed data agents can also serve as the automated building control devices, which connect (via a wired or wireless network) to the switches and control panels.

Low-Level Integration: BIM Standards and Building System Data Protocols

The data acquisition framework proposed in this study assumes that the building systems can provide data in the form of a database, a webpage, or a set of data files (such as a comma-separated

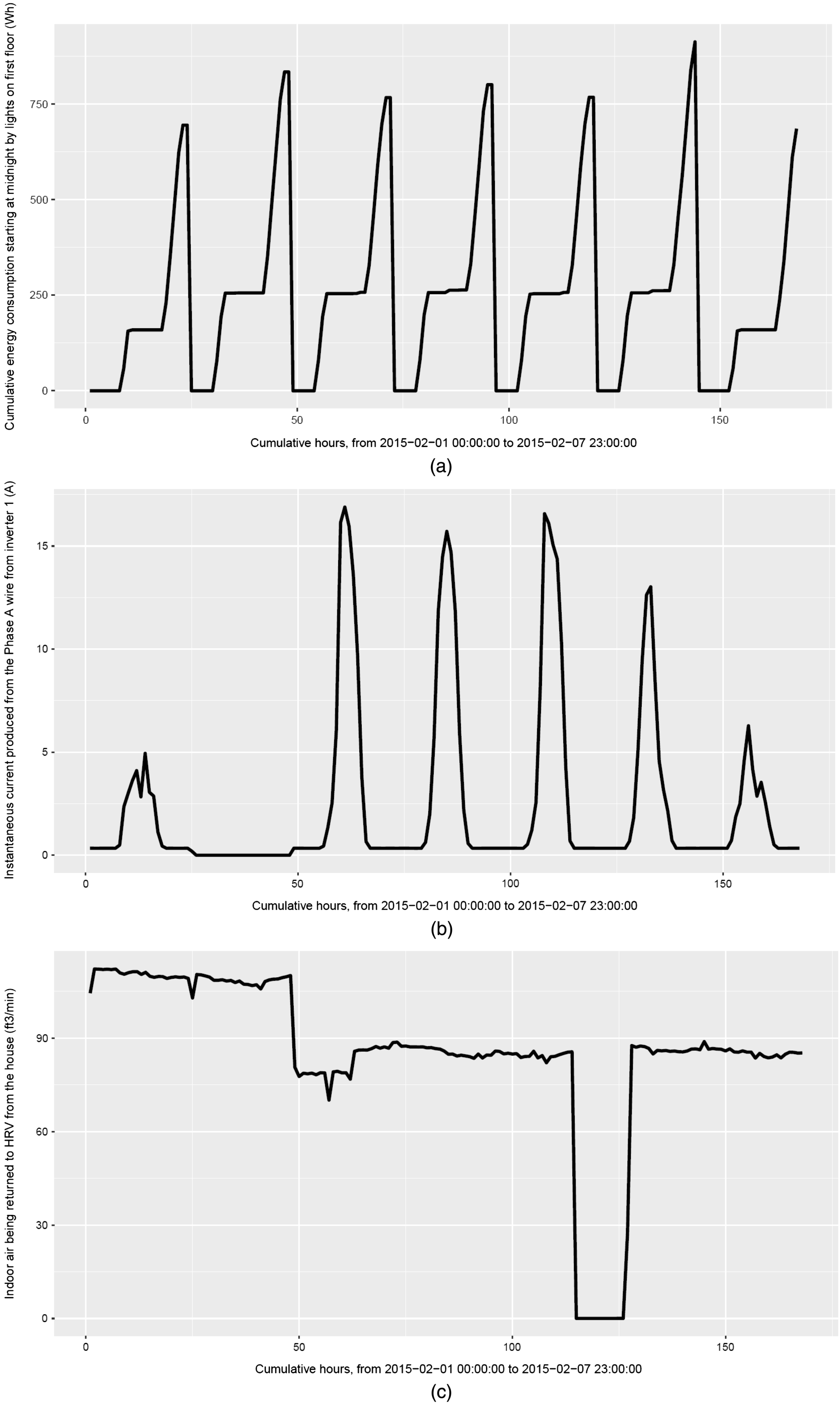
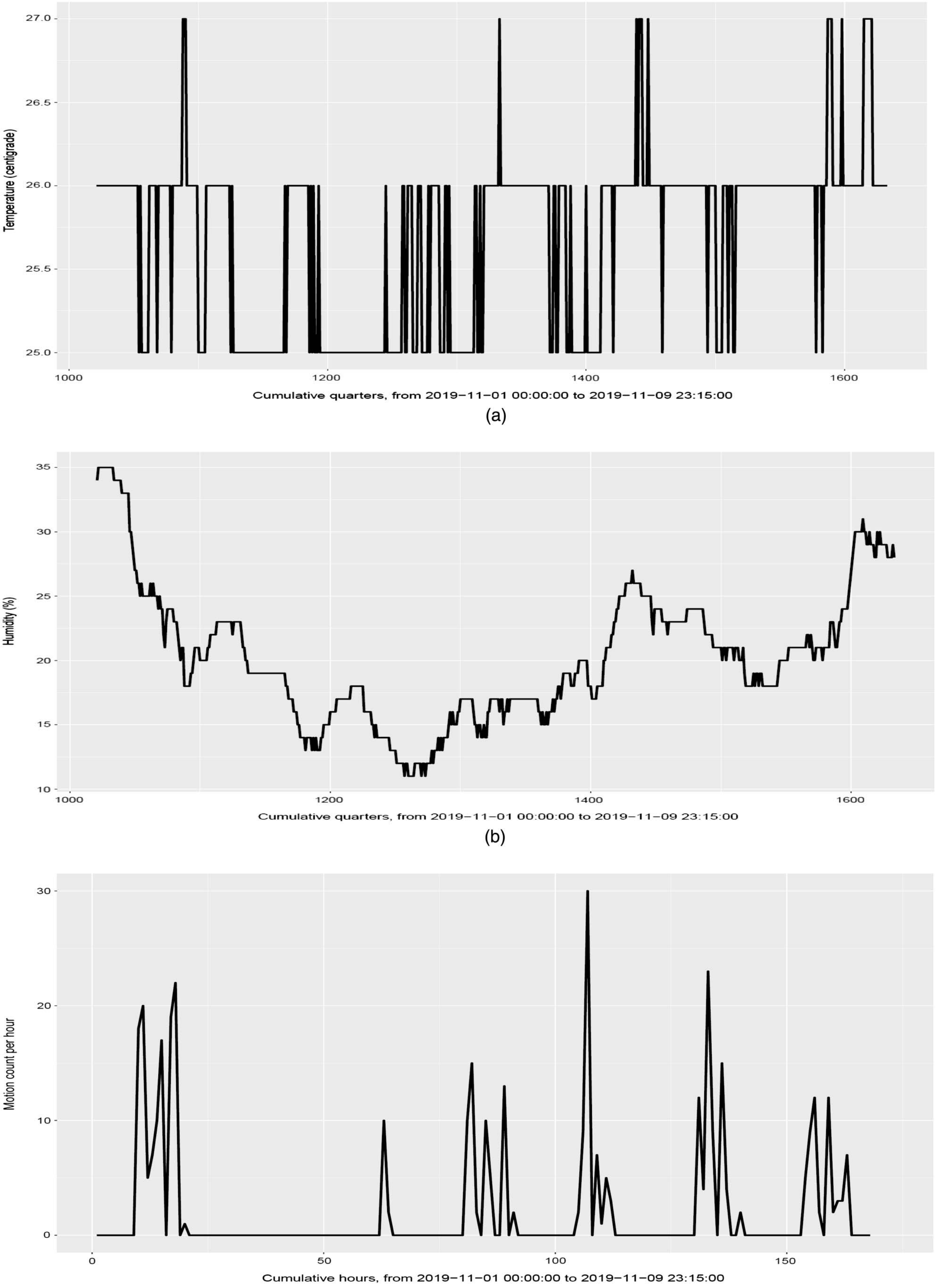


Fig. 10. Example NZERTF data stream visualizations.



(a)

(b)

(c)

Fig. 11. Example indoor environment data stream visualizations.

values file). A potentially more efficient data transaction approach can be achieved by integrating the building data standard and building system data protocols. BIM offers a clear potential as the "digital twin" of the built environment—one that can provide significantly enhanced spatial context for distributed building automation and control systems. A strategy for connecting the building automation and control data protocols with the BIM data schemas can provide a critical layer of spatial semantics to the building systems, such as device geopositioning and metadata tagging, and enrich smart building efforts while harmonizing these data sources with various data protocols.

The connections between the building system data protocols with the BIM data schema can be established by identifying the overlaps between them and creating a federated data framework that enables the data collection, query, and exchange. The research team conducted a research study on facilitating information exchange for BIM-assisted BAS design and operation using one of the BAS open communication protocols called building automation and control networks (BACnet) and open BIM standard Industry Foundation Class (IFC) (Tang et al. 2020). The information delivery manual (IDM) and Model View Definition (MVD) methods were leveraged to define an IFC subset schema (a BACnet MVD) such that BAS information conforming to the BACnet protocol can be represented in the IFC data model for information exchange throughout various project stages with BIM tools.

Vision for the Future Smart City—An IoT Network of Smart Facilities

Based on the IoT-enabled facility data acquisition framework demonstrated in this paper, the authors propose a vision for the future smart city: a network of smart buildings connected by IoT (Gao et al. 2019b). A conceptual IoT-enabled smart city architecture is provided in Fig. 12.

In this IoT-enabled smart city, multiple smart buildings form a community, and many communities—residential community, campus, healthcare, commercial, office, government, and others—form a smart city. In the future, each facility will be "smart" enough to provide a certain amount of real-time data to the city IoT network. The data stream generated in each building through the proposed data acquisition framework is collected by a data hub for each community and then connected to the city-level network. The data contents can vary based on the facility type, but some are universal. The authors call the data that will be provided by all smart buildings "the basic facility data package" (BFDP). The BFDP provides the fundamental data for the smart building network and is the basis of innovative IoT-enabled smart city applications.

In addition to the basic data package, different data will be provided by certain types of facilities, and the authors call them "extra data." For example, healthcare facilities (as indicated in Fig. 12) can provide information pertaining to medical resource availabilities, such as doctors' schedules and the blood bank inventory. They can also send an outbreak alert to the smart city network if an infectious disease case is identified. Another example of extra data is that the supermarket in the smart commercial community (as indicated in Fig. 12) can provide real-time commodity information to the smart city network such that citizens can locate the commodities they need. This function is particularly crucial when natural disasters, such as a hurricane, tsunami, and sandstorm, are threatening the city and citizens are hoarding necessities.

The smart buildings in the proposed architecture not only provide data to the network but also require services from it. The service requirements may vary based on the facility types, but some common services are required by all. The authors call them the

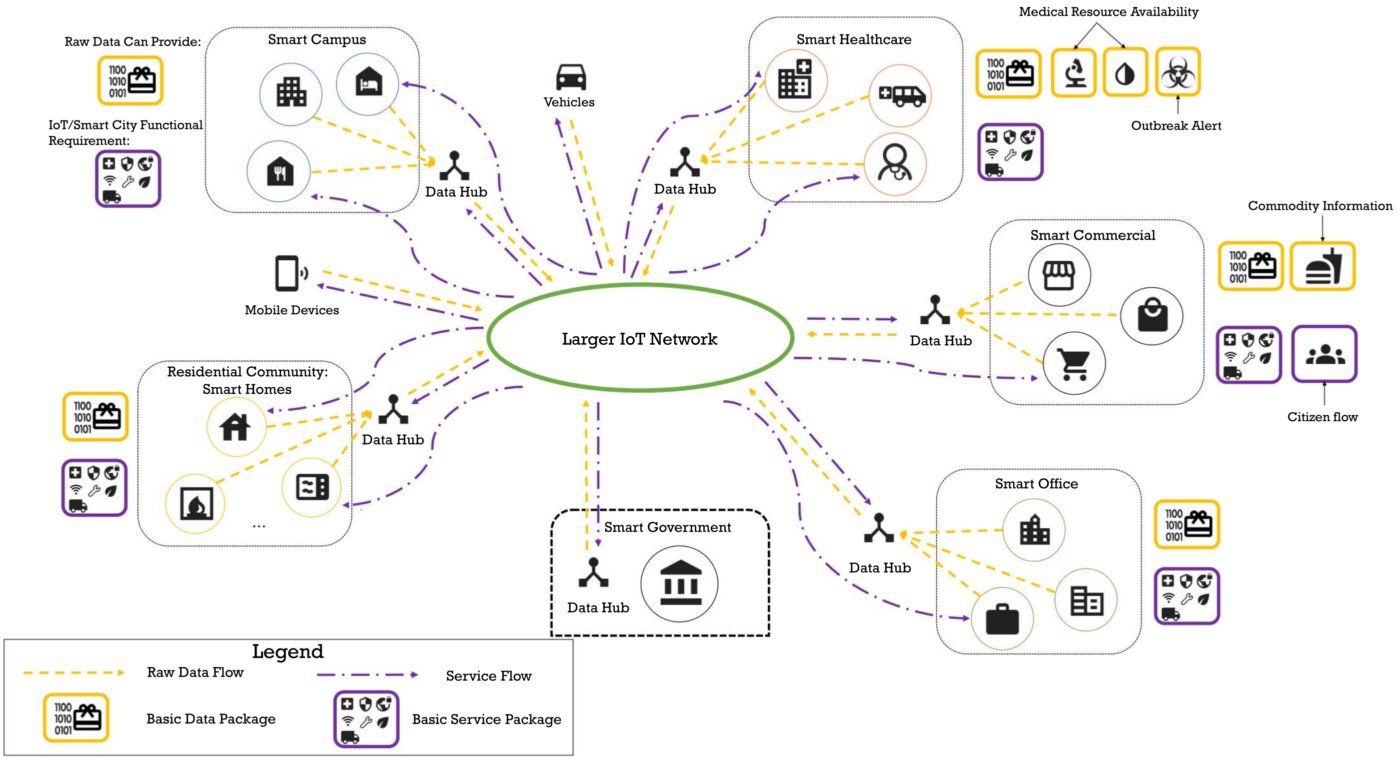


Fig. 12. Architecture of envisioned future smart city. [Icons courtesy of Material.io, licensed under the Apache License, Version 2.0 (http://www.apache.org/licenses/LICENSE-2.0).]

"basic facility service package" (BFSP). Some examples of the BFSP involve security, emergency assistance, data connection, and operation and maintenance. In addition to the BFSP, different services may be requested by certain types of facilities, and the authors call them "extra services." For example, a shopping mall may request real-time citizen flow information from the smart city network to predict customer flow (Fig. 12). The BFDP and the BFSP are evolving over time and may never be exhaustive.

A cyberphysical system (CPS) is the "heart" of this proposed smart city architecture. The physical and digital twins of CPS are reciprocally connected and synchronized in real-time through interconnected sensors and actuators (Gao et al. 2019b). The digital twin of the future smart city will serve as a medium to visualize, simulate, manifest, observe, and control its physical twin (Shelden 2018). The key potential of the future smart city is the infinite horizon it opens for data analytics that can be performed on the digital twin's sensory input, which is constantly "in sync" with what is happening in the physical world. The data analytics enable measuring the city's performance against the city management's targets, which were initially simulated in the digital twin. Thus, these analytics provide a closely coupled feedback loop for assessing the city's effectiveness. In addition, machine learning tools can be utilized to make future predictions of physical performance based on historical data. Ultimately, through CPS, the future smart city could also perform autonomous control and interventions and respond to citizens' needs.

Challenges

Building systems of different vendors are not designed to be semantically and syntactically interoperable (Gao and Pishdad-Bozorgi 2019b). Therefore, extensive software program development work is required to implement the proposed data acquisition framework and, thus, extract data from different building systems with various user interfaces and data access methods. This work is one of the challenges of implementing the proposed framework.

The other challenge is how to guarantee the cybersecurity of the data network—central database, distributed data agents and their local databases, and building systems' internal data—and represents another critical research topic that requires more studies.

Conclusions

This research contributes to the body of knowledge by proposing an IoT-enabled data acquisition framework for smart building innovations. This framework is used for establishing cost-effective, platform-neutral, scalable, and portable building data acquisition systems. The systems utilize the data housed in separate building systems, generate data with low-cost computers and sensor modules, and integrate data stored in distributed databases to establish a central facility database. The authors first propose the conceptual framework, develop a system prototype, and then demonstrate its feasibility and confirm its practical potential using a case study in a campus building.

In the case study, the developed data agents were used to extract a part of the data generated by NZERTF's building systems and to generate and collect the indoor environment data of the studied campus building, respectively. Then, a comprehensive central facility database was established by connecting the databases in the distributed data agents. The results of the case study proved that the proposed framework is effective in using IoT devices and networks to establish a central facility database.

This kind of comprehensive database established through the proposed data acquisition framework enables smart building innovations. In this paper, four use cases of the central facility database are discussed, including facility life-cycle cost analysis with machine learning, improved energy modeling and calibration, occupant status sensing, and data-driven, automated building control. Some research results of the former two use cases are already published (Chen et al. 2019; Gao and Pishdad-Bozorgi 2019a), and the latter two are still in progress.

Opportunities exist for further applications of the proposed data acquisition framework. First, more sensor modules can be installed on the developed data agents to generate and collect more indoor environment data, and more software agents can be developed to extract data from different building systems. Future research can expand the scale of application of the proposed framework. Second, more innovative use cases can be developed using the established central facility database, and more case studies are needed to demonstrate their applicability and effectiveness.

Data Availability Statement

Some or all of the data, models, or code used during the study were provided by a third party (the building system data). Direct requests for these materials may be made to the provider, as indicated in the Acknowledgments.

Some or all of the data, models, or code generated or used during the study are available from the corresponding author by request [(1). the indoor environment data generated in the campus building, and (2). the software agents (Python codes) for data generation, acquisition, and integration].

Acknowledgments

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Supplemental Materials

Additional data are available online in the ASCE Library (www.ascelibrary.org).

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