A Cyber-Physical Middleware Platform for Buildings in Smart Cities

77

Balaji Kalluri, Clayton Miller, Bharath Seshadri, and Arno Schlueter

Abstract

In the realm of smart cities, tools for intelligent, real-time building energy management at the urban-scale are still evolving. Today, most commercial buildings have a dedicated Building Management System (BMS) to manage operations on-site efficiently; but there is no unified approach involving multiple stakeholders to manage them cooperatively in a district or urban scale. Thus, we formulate the following research question: '*What is a feasible structure and what are the relevant components of a middleware that is easy to integrate within existing BMS/EMS and scalable for application in smart cities?*' To address this knowledge gap, this article proposes a new integrated and non-intrusive approach to cyber-physical middleware design using open-source tools. The implementation of proposed middleware in a case study building-scale project in Singapore is presented. Several features are analyzed to understand the relevance and scalability of proposed middleware as a technology enabler for smart building management in cities. The experiences and lessons learned from this project can be extrapolated to the urban-scale as more buildings are equipped with such systems. For this purpose, middleware code is also made available as open-source.

Keywords

Middleware • Building management system • Cyber-physical • 3for2 office

77.1 Introduction

Understanding the multifaceted nature of cities and their underlying components such as building, transportation, and human-interaction is essential to mitigate the impact on climate and to improve the quality of urban life [1]. In the realm of Internet-of-things (IoT), buildings play a critical role in smart cities. Today, most buildings have a dedicated building management system (BMS) to manage operations on-site efficiently; but these processes are often in silos [2]. Typical use-cases of integrated BMS include periodic scheduling of HVAC or lighting loads in buildings for easy monitoring of the indoor environment and remote maintenance. The energy management systems (EMS) on the other hand are focused on collecting sub-hourly meter readings from various end-uses in build-ings. In general, the vendors of these systems often supplement their platform with add-on tools to process and visualize data, but adoption of these technologies has been limited due to a lack of perception of value. Buildings instrumented with sensors, meters, actuators and a BMS constitutes a

B. Kalluri (✉) · B. Seshadri
Future Cities Laboratory (FCL), Singapore-ETH Centre, Singapore, 138602, Singapore
e-mail: kalluri@arch.ethz.ch

B. Seshadri
e-mail: seshadri@arch.ethz.ch

C. Miller
Department of Building, National University of Singapore (NUS), Singapore, 117566, Singapore
e-mail: clayton@nus.edu.sg

A. Schlueter
Architecture and Building Systems (A/S), ETH Zurich, Stefano-Franscini-Platz 1, 8049 Zürich, Switzerland
e-mail: schlueter@arch.ethz.ch

I. Mutis and T. Hartmann (eds.), *Advances in Informatics and Computing in Civil and Construction Engineering*,
https://doi.org/10.1007/978-3-030-00220-6_77

classic example of pervasive sensor networks in the context of built-environment. However, buildings in future shall additionally require intelligent systems that multiplex the role of BMS/EMS for its universal application in smart cities. 'Middleware' is a software layer embedded between the physical hardware and the building system applications that exploit knowledge from the data. Such middleware serves as an intelligent layer in smart building management at urban-scale.

Motivated by the recent growth of urban mobility systems around the world [2], what can smart buildings community learn? How can information from multiple buildings in the urban-scale be collected and processed to enable an effective engagement of stakeholders managing a smart city? The recent developments in Cyber-Physical-System (CPS) enable multiplexing the role of BMS beyond existing building/campus-level management. In Sect. 77.2, we highlight certain limitations of existing middleware for urban-scale building management. In Sect. 77.3, we introduce an approach to develop a non-intrusive, cyber-physical middle-ware to liberate data from a conventional BMS/EMS system in a real building. It integrates the following: (a) a wide range of sensors, meters, and actuators native to building management infrastructure (b) an appropriate cloud-based, centralized database and (c) an intuitive front-end visualization platform. In Sect. 77.4, we discuss how the proposed middleware architecture overcomes existing limitations through our preliminary experiences in collecting, visualizing and analyzing more than two years data using the middleware implemented in the 3for2 office building [3]. The 3for2 project is a 550 sqm, highly instrumented office located in the United World College South-East Asia (UWCSEA) campus in Singapore with 1600 data points from sensors, actuators, meters across multiple zones. An overview of the building capturing specific vital features such as dedicated outdoor air systems for ventilation and passive chilled beams for space cooling are seen in Fig. 77.1. The purpose of this article is two-fold: (a) demonstrate an approach to building such a middleware using open-source tools that allows scalable implementation across buildings in cities; (b) enumerate specific vital features and explore its future application in smart cities.

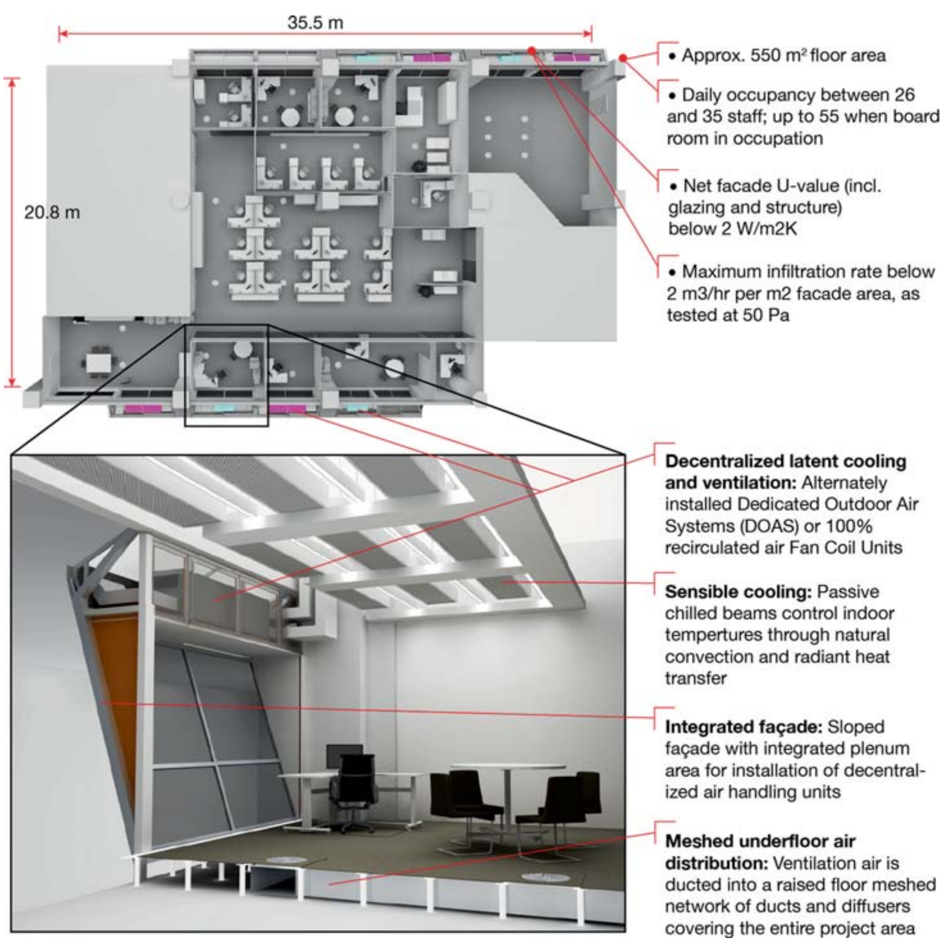

Fig. 77.1 An overview of the 3for2 office space and schematic of the systems installed (adapted from [3] with permission)

77.2 Background and Related Work

Middleware systems for buildings came about the beginning of digital control and automation systems in the 1990s. However, today the growth in IoT and pervasive computing enable cooperation among elements of cyber and physical world leading to a collectively intelligent middleware. Thus, several middleware methods for buildings and cities have emerged in recent years, including but not limited to SensorAct [4] for building energy management and WuKong [5] for virtual IoT/smart city applications. The SmartSantander project [6] is an example of a large-scale implementation of CPS in the city of Santander, Spain. It enables several smart city services such as traffic regulation, monitoring urban environmental quality, parking and irrigation management. However, several challenges still lie open in general.

1. **Lack of integrated middleware:** Building construction and operations management professionals (architects, system engineers, facility managers and technicians) rely on data downloaded from BMS and manipulated spread-sheet programs to visualize spatial and temporal information. The feedback received from them revealed one common concern —'the lack of an integrated middleware' [7]. Some employ multiple BMS and other visualization tools, while other report lack of integration between different building systems, lack of useful visualization of end-use energy data, online dashboard, ability to compare and benchmark multiple building performance ratings.
2. **Data quality and fidelity:** CPS integrates two types of systems which have different assumptions about the lifetime of data [8]. On one hand, data in cyber/computing systems are available until they are modified or deleted, whereas data retrieved from physical systems are valid only at sensed time instance. This situation creates a potential gap in data representation leading to misinterpretation, misuse, and miscomputation.
3. **Lack of open-source, flexible middleware for buildings in cities:** Intelligent building energy management in neighborhood and cities require a scalable data-acquisition, processing, and visualization middleware. Sakakibara et al. [8] elucidates the lack of a flexible middleware whereby the application developers of CPS/IoT systems for smart buildings and cities are constrained by which sensors and how many sensors have to be deployed in buildings. Arjunan et al. [4] demonstrates the application of an open-source, decentralized middleware for buildings called SensorAct, which requires additional dedicated devices (e.g., gateways) for smart energy management. The middleware such as SensorAct, on the one hand, proves appropriate for fine-grained energy management in building-scale, but on the other hand is intrusive and lacks scalability with additional hardware devices for managing several buildings across city-scale.

In some cases, the architecture of these middlewares are developed with a relatively narrow scope: to control systems within buildings [4] or collect necessary information regarding the operation of buildings [8]. These limitations suggest a knowledge gap in existing middlewares towards intelligent energy management (both demand and supply) across several buildings in a city. Motivated by these open challenges, we formulate the following research question '*What is a feasible structure and what are relevant components of a middleware that is easy to integrate within existing BMS/EMS and scalable for application in smart cities?*' with a particular focus on future smart and sustainable urban-scale building management.

77.3 Development of the Cyber-Physical Middleware

Typically, cities have several hundreds of buildings, and every building is made up of several levels and zones. The BMS enables monitoring buildings to improve overall management. Typically, it includes sensors and actuators for monitoring and controlling energy and IEQ. The integrated BMS aid in managing all building services through a unified platform. This approach is generally made at a building or neighborhood-scale. However, managing several buildings in cities require a non-intrusive approach to extract, store, process and visualize essential building information. This section presents an approach to implement such a middleware in the *3for2* office building [3].

A simplified schematic representation of the flow of information from buildings in urban-scale is illustrated in Fig. 77.2. It describes the role of the proposed middleware in creating expert insights about buildings from sensor data together with data-aware end-use applications. The data from several buildings in the UWCSEA campus including the 3for2 office is continuously monitored, collected and stored locally using an integrated commercial BMS from Siemens Building Technologies. The REST API [9] interface of BMS is used for non-intrusive collection of data from multiple building in the campus. The middleware is termed *Cyber-Physical* because it bridges information from the physical world of sensors in buildings with the cyber-world using cloud computing technology. Its *integrated* architecture combines a centralized,

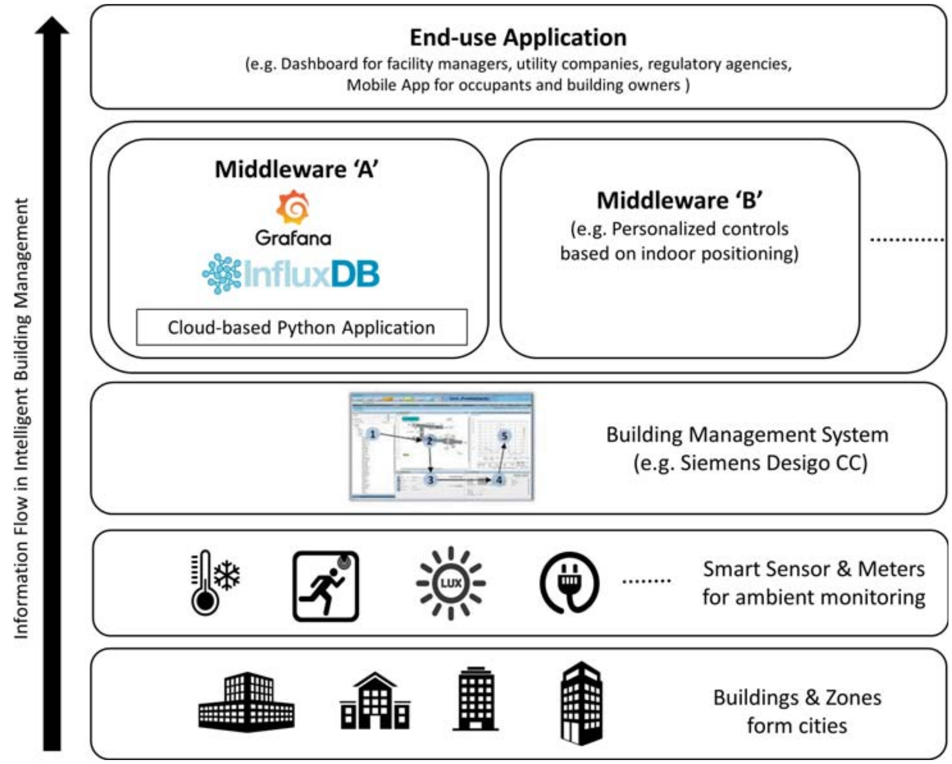

Fig. 77.2 Information flow using proposed middleware: From data to knowledgeable in-sights

cloud-based Python application to collect streaming data from sensors (in the physical world) into a modern time-series database called Influx DB [10], and further visualize using an intuitive open-source platform called Grafana [11]. Several visualization prototypes were developed to interface with the InfluxDB platform, including a time-series monitoring application in Grafana which enables intuitive, fast navigation and visualization of data. Other more customized dashboards were developed using JavaScript. The middleware architecture is *non-intrusive* in the sense that it collects data across multiple buildings without the need for additional devices such as gateways using a secure and straightforward Python application. It is used to create a small query engine that calls the API at a specific frequency, processes the data, and sends it to a cloud database. This database technology was developed specifically for time-series data and is much faster at ingesting and serving these data as compared to conventional SQL technologies. It is also an integrated platform as it converges BMS/EMS capabilities, with efficient cloud-storage and advanced visualization, all from discrete cloud-services onto a centralized platform. This application is made open-source on project GitHub repository[1] for wide-scale deployment and validation.

77.4 Analysis and Discussion

77.4.1 Case Study of 3for2 Office Building

The implementation of the proposed middleware in the *3for2* office building enabled us to overcome particular challenges. The analysis presented in this section help understand them through specific examples.

Flexibility in data representation: Ability to cope with non-homogeneous sampling intervals offered by the underlying hardware, without loss of information is critical to decision-making in IoT enabled smart buildings and cities. The proposed middleware handles this gap diligently. The choice of appropriate components of middleware (e.g., InfluxDB and Grafana) to store streaming data from several sensors help effectively collect, manage and present temporal data streams. The power consumption data of a low-lift chiller (LLC) in the 3for2 office for a week on February 18 is presented as an example for analysis in Fig. 77.3. In this example, estimated weekly energy consumption (in kWh) of LLC based on either 1-minutely or

[1]Siemens-InfluxDB Middleware Repository https://github.com/architecture-building-systems/desigo-influxdb-middleware.

Fig. 77.3 Comparison of electrical power consumption profiles of a low-lift chiller compressor and it's corresponding daily energy consumption represented as bar-charts for a week in Feb.'18 based on **a** 1-hourly trends **b** 1-minute trends

1-hourly sampling is same (approx. 103 kWh). It demonstrates visualizing information (by either minutely or hourly) from a physical system without information loss is possible irrespective of the rate of sampling. Thus, illustrating the integrity of using information retrieved and stored in the middleware.

Ease of managing and querying building information: Physical component such as sensors, meters, and actuators present a meaningful picture of the indoor condition of a building over time. To the best of our knowledge, accessing and managing this information at a city or district scale was previously incomprehensible due to the complexity in organizing various data streams into meaningful hierarchies and understanding them in the right context. The integration of BMS and the middleware in the 3for2 project simplifies this complexity in managing and querying discrete information at either system or component-level in a building. For this purpose, a meta-data file for instrumented physical components in the building is prepared. Such a meta-data file includes information regarding the system it serves together with its digital identity, their physical location within the building, building within a neighborhood/city and so on. Thus, the proposed middleware integrated with REST API of BMS enable automatic retrieval of large volumes of building information on-the-fly. Further, this facilitates dynamic and non-intrusive visualization of building information, without them having to know about sensor placement inside buildings. Examples of such information in building-scale include energy breakdown by end-use/zones and overall daily/weekly/monthly energy-use-intensity. In the future, such a middleware shall enable comprehension and visualization of abstract information of buildings and systems in cities (e.g., the fraction of energy consumed from on-site renewables by different buildings in a neighborhood) which was earlier deemed unmanageable.

Understanding meaning behind data patterns: The proposed middleware integrated with BMS in the 3for2 office building enable using specific meta-data information to configure data dashboards. Some examples include information about the 'nature of end use systems' such as HVAC, lighting and plug-load; or about the 'physical measured quantity' such as energy (in kWh), cooling load (in RT); or about the 'physical location inside a building' such as plant room, Area 3for2, Level 7; or about the 'physical instances' annotating the number of identical sensors in that zone. The front-end visualization tool (Grafana) integrated into the proposed middleware allows easy visualization of temporal data patterns across buildings or zones within buildings. It also improves understanding the data in the right context of built-environment using well-annotated

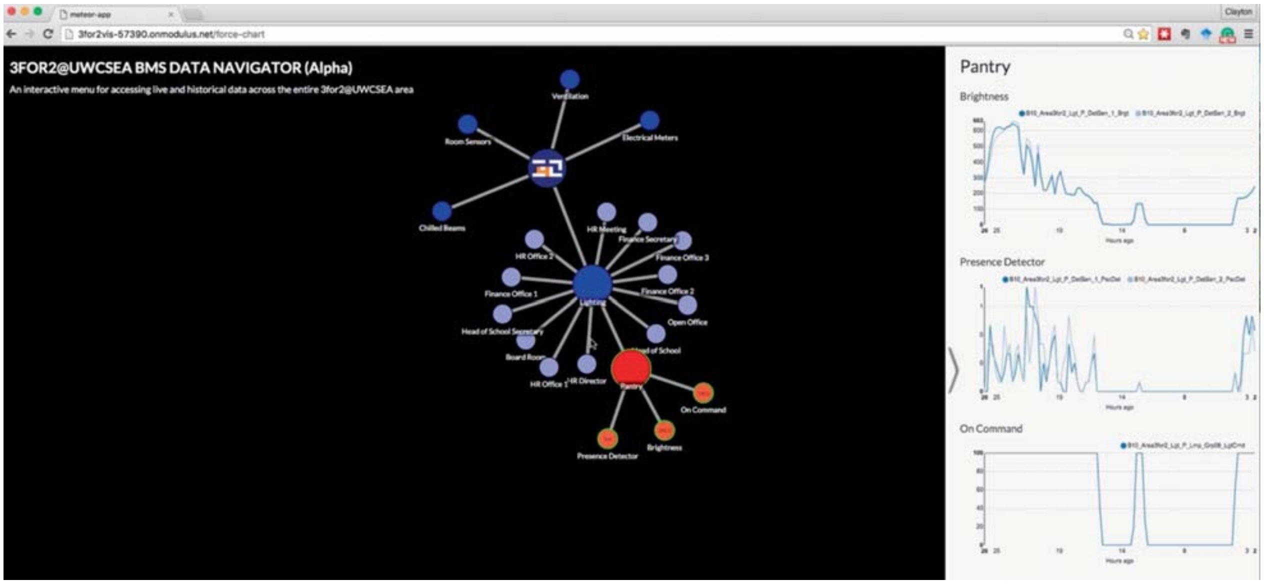

Fig. 77.4 A node-based prototype designed to allow fast navigation of sensor networks

meta-data tags. This approach facilitates stakeholders to take decisions by understanding the implications, limitations, and boundaries of data being collected. Further, a node-based visualization prototype is presented in Fig. 77.4. It was created to test an overview, zoom and filter, details-on-demand concept that is common in the visual analytics community of research, whereby users can select various nodes in the hierarchy and expand them level-by-level. At a certain depth, the detailed temporal data is visualized for the subset of points as a line chart or heat map. These techniques illustrate the notion of 'data-aware' over 'data-driven' design suggested by Bates et al. [2].

77.4.2 Middleware as Smart Building Sensing Service in Cities

In the urban-scale building management, several stakeholders will potentially be interested in the energy-use information. For example, a city/municipal council may use information about on-site renewables together with energy demand from buildings in a neighborhood to device policies, initiatives and rewards to influence communities towards more sustainable and energy-aware lifestyle. Additionally, construction authorities may use the information to classify and benchmark of buildings based on energy demand instead of their end-use type, which is more appropriate and rational. Further, utility companies shall benefit regarding demand-aware generation, distribution, scheduling and pricing of energy such that they avoid black-outs during episodes of peak demands. Finally, building owners can make more informed decisions on when and how much to trade their on-site energy with the grid. The proposed middleware thus enable seamless information flow between buildings and urban systems stakeholders. Based on our experience in successfully implementing a non-intrusive, integrated middleware using open-source tools for a building at neighborhood-scale, we extrapolate sensing and managing buildings to urban-scale using an existing *Smart Building Sensing as Service* (SBSS) model [12] in this section.

A Future Scenario: A Potential Future Application of the Proposed Cyber-physical Middleware
Let us consider a situation where building owner 'C' learns about his building energy information (BIPV generation = 10 kWh, on-site storage available = 25%, end-use consumption = 5 kWh) together with electricity tariffs from the utility grid and his neighbors through SBSS platform (Fig. 77.5). He then decides to sell his excess on-site generated (green) energy and publishes the tariffs to the cloud. Similarly, building owner 'A' also publishes his tariffs. An intelligent cloud-based bidding application sitting on top of the proposed middleware will federate bidding process between several stakeholders. Building owner 'B' predicts her building energy consumption to exceed beyond on-site generated and decides to buy (green) energy from its neighbors over energy from (fossil-based) utility grid for several reasons (e.g., environmental impact, energy pricing). Similar to buildings, a city council which manages operations like street lighting, and public park irrigation may also participate in bidding for (green) energy through the proposed platform (Step 4). It is important to note that entire

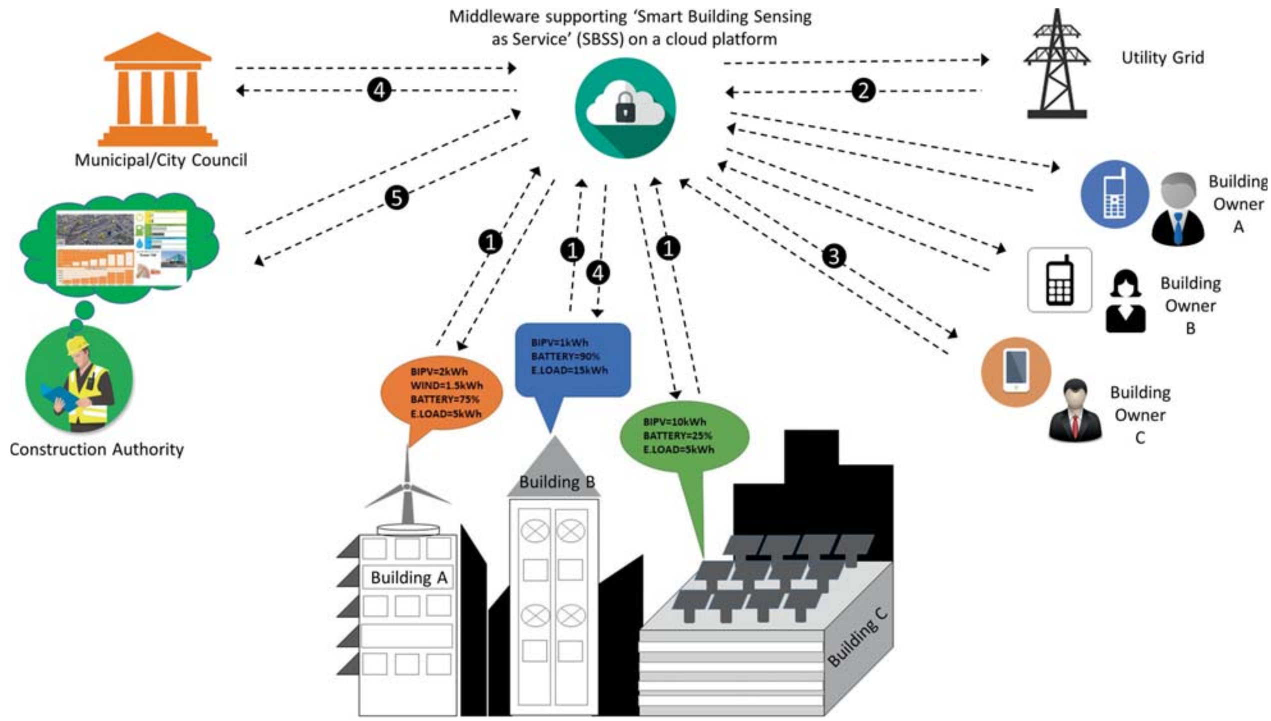

Fig. 77.5 A future scenario—smart building sensing as service model for cities

electrical energy exchange is facilitated jointly by the middleware and bidding application which are part of the smart-grid infrastructure. Finally, construction authorities who plan urban (re)development and public works shall also benefit visualizing key building information (e.g., energy usage, on-site generation, energy purchasing trends) from across several buildings to intelligently rank buildings reflecting their true energy performance. Currently, building authorities rely on rating systems such as GreenMark and LEED which are based on annual energy reports submitted by building owners and ESCO's which in future will be in near real-time.

77.5 Conclusion, Limitation and Future Work

A new cyber-physical approach to develop a non-intrusive and integrated middleware based on open-source tools to manage buildings in future cities is introduced. The middleware extends the capabilities of a commercial BMS into a far more reliable and desirable solution in the building management industry. The potential of the proposed middleware is demonstrated through a successful implementation in the *3for2* office building in Singapore. Several features are analyzed to understand the relevance and scalability of proposed middleware as a technology enabler for smart building management in cities. Collectively, all the features make it suitable for scaling and replicating across more buildings in future. For this purpose, the middleware code is also made publicly available as open-source. The sustainable management of buildings in urban-scale is not far from reality, as building construction industry has already taken steps forward by embracing web-technologies and IoT. We conclude with an example use-case scenario that elucidates how the middleware enables a future potential SBSS model for cities.

Acknowledgements The authors would like to extend our sincere thanks to Siemens Building Technologies and UWCSEA facilities management team for their support.

References

1. Crooks, A., Schechtner, K., Dey, A.K., Hudson-Smith, A.: Creating smart buildings and cities. IEEE Pervasive Computing **16**(2), 23–25 (2017). https://doi.org/10.1109/mprv.2017.23
2. Bates, O., Friday, A.: Beyond data in the smart city: repurposing existing campus IoT. IEEE Pervasive Computing **16**(2), 54–60 (2017). https://doi.org/10.1109/mprv.2017.30
3. Schlueter, A., Rysanek, A., Miller, C., Pantelic, J., Meggers, F., Mast, M., Bruelisauer, M., Chen, K.W.: 3for2: Realizing spatial, material, and energy savings through integrated design. CTBUH J. **II**, 40–45 (2016)
4. Arjunan, P., Saha, M., Choi, H., Gulati, M., Singh, A., Singh, P., Srivastava, M.B.: SensorAct: A decentralized and scriptable middleware for smart energy buildings. In: 15th UIC-ATC-ScalCom Conference, pp. 2767–2774. IEEE, Beijing (2015). https://doi.org/10.1109/uic-atc-scalcom-cbdcom-iop.2015.27
5. Shih, C.-S., Chou, J.-J., Lee, K.-H., Lin, K.-J.:Data-Driven IoT applications design for smart city and smart buildings. In: UIC/ATC/ScalCom/CBDCom/IoP/SmartWorld Conference. In-press. IEEE, San Francisco (2017)
6. Sanchez, L., Muoz, L., Galache, J.A., Sotres, P., Santana, J.R., Gutierrez, V., Ramdhany, R., Gluhak, A., Krco, S., Theodoridis, E.: SmartSantander: IoT experimentation over a smart city testbed. Comput. Netw. **61**, 217–238 (2014). https://doi.org/10.1016/j.bjp.2013.12.020
7. Shih, C.-S., Chou, J.-J., Reijers, N., Kuo, T.-W.: Designing CPS/IoT applications for smart buildings and cities. IET Cyber-Phys. Syst. Theory & Appl., **1**(1), 3–12 (2016). https://doi.org/10.1049/iet-cps.2016.0025
8. Sakakibara, S., Saiki, S., Nakamura, M., Matsumoto, S.: Indoor environment sensing service in smart city using autonomous sensor box. In: Computer and Information Science (ICIS), 2016 IEEE/ACIS 15th International Conference on, pages 1–6. IEEE, Okayama (2016). https://doi.org/10.1109/icis.2016.7550871
9. Fielding, R.T., Taylor, R.N.: Architectural styles and the design of network-based software architectures. Doctoral Dissertation, University of California, Irvine (2000)
10. InfluxDB Database Github Repository. https://github.com/influxdata/influxdb
11. Grafana Github Repository. https://github.com/grafana/grafana
12. Perera, C., Zaslavsky, A., Christen, P., Georgakopoulos, D.: Sensing as a service model for smart cities supported by internet of things. Trans. Emerg. Telecommun. Technol., **25**(1), 81–93 (2014). https://doi.org/10.1002/ett.2704