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A conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building : A case study in Hotel ICON of Hong Kong

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Abstract

This study proposes a conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building, focusing on the energy-efficient, occupant-oriented, and comfortable indoor environment. The proposed framework aims to improve the energy efficiency in a room of building while achieving the healthy and comfortable indoor environmental quality and occupants' satisfaction. The proposed framework consists of a three-phase cyclic process (i.e. monitoring, diagnostic, and intervention), and it can be simply replicated and extensively applied to the different levels of physical entities (spatial scalability) in the different time resolutions in the whole life cycle processes (temporal scalability). To elaborate the feasibility of the proposed framework, the Hotel ICON in Hong Kong are chosen as a case study. For three rooms in the Hotel ICON, several sensors are installed for monitoring the energy efficiency and indoor environmental quality in real time. With the collected dataset, it is planned to carry out the diagnostic process (e.g. anomaly detection, time-series analysis, and occupancy schedule pattern analysis) and the intervention process (e.g. automatic control, occupant behaviour change, and optimal operation). The conceptual framework provides a standardized and systematic research approach toward a big picture of an intelligent building systems for the energy-efficient, occupant-oriented, and comfortable indoor environment.

Keywords: Real-time monitoring and diagnostic; Energy efficiency; Indoor environmental quality; Occupant satisfaction; Optimal operation

1. Introduction

As an imperative issue to be settled, a global warming has been the major target in the United Nations Framework Convention on Climate Change (UNFCCC). The Chinese government has proposed that the CO_2 emission per unit

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of gross domestic product (GDP) in 2030 will be reduced by 60-65% from that in 2005 [1]. Since the building energy consumption makes up a proportion of 30% of the global energy consumption [2], there exists the large amount of energy conservation potential in the building sector. The Hong Kong Green Building Council (HKGBC) has launched the "HK3030" campaign so as to reduce the absolute building electricity consumption in 2030 by 30% from that in 2005. Meanwhile, occupants spend 80–90% of their time inside buildings [3]; and thus, the indoor environmental quality (IEQ) plays a vital role on occupants' health, satisfaction and working productivity. In this regard, it is a tough mission to maintain the satisfied IEQ while reducing energy consumption in buildings [4].

The innovative technologies such as nonintrusive monitoring (NILM) technique, information and communication technologies (ICTs), and computing technologies have been rapidly developed. Even if many studies tried to improve energy efficiency, IEQ and occupant satisfaction by implementing the real-time sensor network [5-17], they have focused on one-side aspect and have lack of generality. Therefore, it is necessary to develop the novel approach to simultaneously take into account energy efficiency, IEQ and occupant satisfaction, in which the logical process of identification-analysis-solution should be proposed.

To overcome these challenges, this study aims to develop a conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building, focusing on the energy-efficient, occupant-oriented, and comfortable indoor environment. The proposed framework includes a modularized research unit that can be applied to the different levels of physical entities (spatial scalability) in the different time resolutions in the whole life cycle processes (temporal scalability). The Hotel ICON in Hong Kong are chosen as a case study in order to elaborate the feasibility of the proposed framework.

2. Conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building

According to the Intelligent Planning Unit (IPU) theory [18-19], the proposed framework is expected to achieve the goal of energy saving, IEQ improvement and occupant satisfaction in a strategic manner (i.e. spatial-temporal scalability). As shown in Figure 1, the proposed framework can be explained in two parts: (i) research unit and (ii) research process (i.e. three-phase cyclic process; monitoring-diagnostic-intervention).

2.1. Research unit

As mentioned above, it is required to consider the energy efficiency, IEQ improvement, and occupant satisfaction within the same context. Using real-time sensors, it is possible to collect the real-time bigdata for energy efficiency and IEQ, which can be centralized to the cloud server via the Internet of Things (IoT) technology. The bigdata can be analyzed via data mining techniques (i.e. artificial intelligence (AI) and machine learning). Occupant satisfaction can be measured by subjective judgment (i.e. questionnaire survey). As for the virtual reality (VR) and augmented reality (AR) techniques, they can be used for the investigation on influential factors of occupant satisfaction.

2.2. Three-phase cyclic process

With the concept of the "dynamic approach" [20], the three-phase cyclic process (i.e. monitoring-diagnostic-intervention, refer to Figure 2) can be applied to the energy efficiency, IEQ improvement and occupant satisfaction.

First, in the monitoring phase, the real-time sensor network (i.e. objective field measurement) can be used to collect the information on the building performance (i.e. energy efficiency and IEQ improvement). In addition, the questionnaire survey (i.e. subjective approach) can be used to collect the information on the occupant satisfaction. Based on the collected bigdata, the potential problems in buildings can be intuitively and systematically identified, and they can be used in the following phases of diagnostic and intervention.

Second, in the diagnostic phase, the problems identified in the monitoring phase will be analyzed in detail via data mining techniques (e.g. case-based reasoning, artificial neural network, support vector machine) and statistical analysis (e.g. time-series analysis, regression analysis). After diagnosing the "disease" included in buildings that could be obstacles to achieve the energy efficiency, IEQ improvement, and occupant satisfaction, the proper "remedy" can be applied in the intervention phase. The research items can be explained in details as follows.

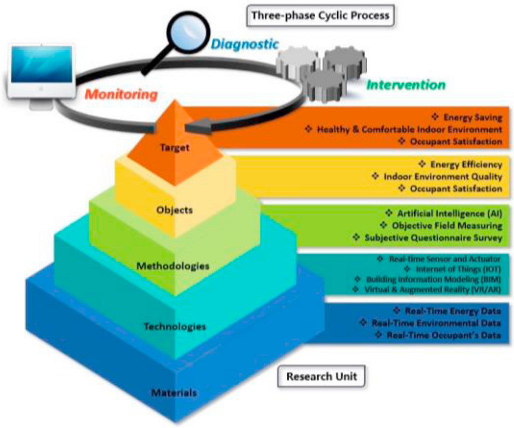

Figure 1. The conceptual framework of the real-time monitoring and diagnostic system for the optimal operation of smart building

- *Anomaly Detection*. It can be used to detect the inconsistent operational mode of electric appliances or indoor environmental indicators (i.e. out of the prescribed range in guidance note [21]), which can occur by deteriorating appliance and occupant behavior error. Pattern recognition techniques (e.g., *K-means* clustering algorithm), machine learning techniques (e.g., artificial neural network algorithm), and outlier detection method (e.g., generalized extreme studentized deviate algorithm) can be used to detect anomalous condition.
- *Time-Series Analysis*. It can be used to estimate the future energy consumption and indoor environmental indicators. This can be conducted with a certain time period of dataset, including energy consumption, indoor environmental indicators, and the influential factors (e.g., indoor air temperature and outdoor air temperature). Significance test (e.g., t-test and Analysis of Variance (ANOVA)), linear prediction model (e.g., Autoregressive Integrated Moving Average Model (ARIMA)), and nonlinear prediction model (e.g., advanced case-based reasoning) can be used, or hybrid model (e.g. ARIMA and advanced case-based reasoning) can be developed.
- *Occupant Schedule Pattern Analysis*. Some behavior patterns can be identified by taking into account of proxy indicators. For example, the variation of indoor temperature and CO_2 concentration can be used to determine the on/off condition of HVAC system and occupancy condition of a room, respectively. For the confidential issue, it is not allowed to monitor the occupant behavior directly by cameras or motion sensors on a large scale and for a long time. Under such circumstances, indirect indicators (e.g. CO_2 concentration) that correlate with occupant motions [9, 10] can be used to predict behavior patterns by pattern analysis and machine learning techniques.

Third, in the intervention phase, the optimal control strategy can be developed and validated by agent-based modelling, machine learning and optimization techniques. The potential research items are as follows.

- *Automatic Control*. On the one hand, the operational schedule of electric appliances to shift peak load can be determined by Active Demand-Side Management (ADSM) system rather than occupants' direct control. On the other hand, depending on the practical requirement level or the minimum satisfaction level for IEQ indicators, the automatic controllers (e.g. thermostat and humidistat) can be implemented to adjust the indoor environment quality in real time, which can save the unconscious amount of energy consumption.
- *Occupant Behavior Change*. The optimal operations of electric appliances can be managed by machine learning algorithm and optimization algorithm (e.g. genetic algorithm) to shift the peak load. With the intuitive index (e.g. operational rating) set in the previous two stages (i.e., monitoring and diagnostic), the logical feedback process can be used to help occupants to change their behavior in an easier and more efficient way.

3. Spatial-Temporal Scalability

The proposed conceptual framework is expected to be extensively used for the specific purpose and functions on its own unit or by cooperating with other similar units. In addition, it can be simply replicated at the different levels of physical entities (spatial scalability) in the different time resolutions in the whole life cycle processes (temporal scalability), namely spatial-temporal scalability.

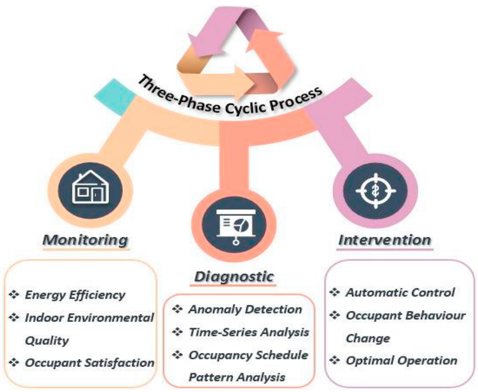

Figure 2. Three-phase cyclic process of the proposed framework

For the spatial scalability (refer to Figure 3), a research unit can be scaled up from room-scale to world-scale, in order to save energy while improve indoor environmental quality for occupant satisfaction. In this process, the emerging techniques like IOT can contribute to acquiring the sufficient measurement and the relevant comprehensive knowledge from a holistic view.

For the temporal scalability, the real-time data can be collected and aggregated within a certain interval (e.g. 1 minute and 15 minutes). However, it is not always true that the more accurate and useful results can be obtained with the higher time resolution because of the outliers and overfitting problem. In this regard, the time resolution needs to be considered in accordance with the project characteristics.

4. Case study

To illustrate the feasibility of the proposed framework, Hotel ICON in Hong Kong was selected as a case study, of which three tomorrow guestrooms were used for the real-time data collection (i.e. energy and environment).

4.1. Real-time data collection

The real-time data on electricity consumption and indoor environmental indicators were collected from April through May in 2018. The electricity consumption was measured by EnerTalk sensors in 15-minute interval. Apart from the overall electricity consumption of each room, the electricity consumption from individual appliances (i.e., television, refrigerator, fan-coil unit (FCU), guest room lighting, bathroom lighting and emergency lighting) were also measured. The indoor environmental indicators, including temperature, relative humidity, CO_2 concentration, chemical concentration, and dust concentration, were measured by Awair sensors in 15-minute interval. Considering that the real-time data were collected from a single guestroom, each of guestrooms can be defined as a research unit. In this regard, the following sections also focused on a single guestroom, and a room 1014 was used as an example.

Figure 3. The spatial scalability of the proposed framework

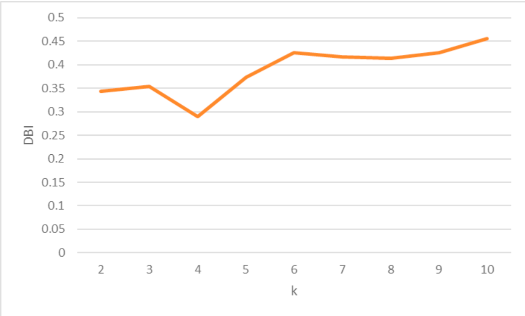

Figure 4. The clustering performance evaluation of different number of clusters by DBI

4.2. Operation pattern analysis for FCU

The component of power consumption in FCU is fan. The amount of energy in FCU depends on the different fan speeds. In general, FCU is operated in four levels of fan speeds (i.e. high, middle, low and stop), and it can be controlled both automatically and manually: (i) it can be controlled centrally by the building energy management system (BEMS); and (ii) it can be controlled via control panel in each room by occupant's preference. Considering the privacy issue, it is hard to directly obtain the operation pattern of FCU (i.e. fan speed of FCU). Thus, the unsupervised learning method was applied to estimate the operation pattern of FCU.

The k-means clustering method, which is one of the widely used unsupervised learning methods [22-24], was conducted to classify the 15-minute energy consumption patterns of FCU in room 1014 so that the operation pattern of FCU could be estimated. The Davies-Bouldin Index (DBI) was used to evaluate the clustering performance, in which the lower DBI value represented the better clustering performance. In this regard, the number of clusters was determined by identifying the lowest value of the DBI. For the clustering and DBI calculation, this study used RapidMiner Studio Version 8.2. Figure 4 shows the DBI with different number of clusters, and the lowest value of the DBI corresponded to the number of clusters (i.e. four clusters).

As a result, the 15-minute energy consumption patterns of FCU in room 1014 were divided into four clusters, and the detailed values of each cluster are shown in Table 1. The four clusters were considerably matched to the general operation status of FCU (i.e. high, middle, low and stop), and these four clusters were quite evenly distributed. It indicated that the guests or BEMS in 1014 were likely to control the fan speed of FCU in four levels.

Meanwhile, it can be said that the FCUs in other rooms have been properly operated in four normal status. Instead, it is possible that the FCUs in other rooms have been only operated in part of speed levels due to the individual preference of guests or the malfunction of FCU and BEMS. In this regard, the operation pattern analysis for FCU needs to be conducted to other two rooms (i.e. room 1015 and 1016) so as to check the working conditions.

Table 1. Clustering results in room 1014

Status	15-minute energy consumption	Number	Ratio (%)
Stop	0.74	1576	37.31
Low	7.06	776	18.37
Middle	16.55	951	22.51
High	22.4	921	21.80

5. Conclusion

This study aims to develop a conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building, in which the three-phase cyclic process are well defined with the concept of the spatial-temporal scalability. In the spatial aspect, it can cooperate with other units in the identical structure and it can be extended to the broader level. In the temporal aspect, it can be applied in the whole life cycle processes with the appropriate time resolution. The conceptual framework is applied to the Hotel ICON in Hong Kong to show its feasibility (operation pattern analysis for FCU anomaly detection). The proposed framework is a well-defined concept that can realize a big picture of an intelligent building systems for the energy-efficient, occupant-oriented, and comfortable indoor environment.

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References

[1] National Development and Reform Commission, Comprehensive Work Plan for Conserving Energy and Reducing Emissions for The Thirteenth Five-year Plan (National Development and Reform Commission), in, 2016.
[2] D. Yan, W. O'Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, A. Mahdavi, Occupant behavior modeling for building performance simulation: Current state and future challenges, Energy and Buildings, 107 (2015) 264-278.
[3] I. Sarbu, C. Sebarchievici, Aspects of indoor environmental quality assessment in buildings, Energy and Buildings, 60 (2013) 410-419.
[4] J. Kim, T. Hong, J. Jeong, M. Lee, M. Lee, K. Jeong, C. Koo, J. Jeong, Establishment of an optimal occupant behavior considering the energy consumption and indoor environmental quality by region, Applied Energy, 204 (2017) 1431-1443.
[5] J.-S. Chou, A.S. Telaga, Real-time detection of anomalous power consumption, Renewable and Sustainable Energy Reviews, 33 (2014) 400-411.
[6] J.-S. Chou, A.S. Telaga, W.K. Chong, G.E. Gibson, Early-warning application for real-time detection of energy consumption anomalies in buildings, Journal of Cleaner Production, 149 (2017) 711-722.
[7] T. Sharmin, M. Gül, X. Li, V. Ganev, I. Nikolaidis, M. Al-Hussein, Monitoring building energy consumption, thermal performance, and indoor air quality in a cold climate region, Sustainable Cities and Society, 13 (2014) 57-68.
[8] V. De Giuli, R. Zecchin, L. Salmaso, L. Corain, M. De Carli, Measured and perceived indoor environmental quality: Padua Hospital case study, Building and Environment, 59 (2013) 211-226.
[9] M.S. Zuraimi, A. Pantazaras, K.A. Chaturvedi, J.J. Yang, K.W. Tham, S.E. Lee, Predicting occupancy counts using physical and statistical Co 2 -based modeling methodologies, Building and Environment, 123 (2017) 517-528.
[10] M. Luoma, S.A. Batterman, Characterization of particulate emissions from occupant activities in offices, Indoor air, 11 (2001) 35-48.
[11] Z. Yu, F. Haghighat, B.C.M. Fung, E. Morofsky, H. Yoshino, A methodology for identifying and improving occupant behavior in residential buildings, Energy, 36 (2011) 6596-6608.
[12] C. Ivanov, L. Getachew, S.A. Fenrick, B. Vittetoe, Enabling technologies and energy savings: The case of EnergyWise Smart Meter Pilot of Connexus Energy, Utilities Policy, 26 (2013) 76-84.
[13] K. Zhou, C. Yang, J. Shen, Discovering residential electricity consumption patterns through smart-meter data mining: A case study from China, Utilities Policy, 44 (2017) 73-84.
[14] W. Gans, A. Alberini, A. Longo, Smart meter devices and the effect of feedback on residential electricity consumption: Evidence from a natural experiment in Northern Ireland, Energy Economics, 36 (2013) 729-743.
[15] M. Rodríguez Fernández, A. Cortés García, I. González Alonso, E. Zalama Casanova, Using the Big Data generated by the Smart Home to improve energy efficiency management, Energy Efficiency, 9 (2015) 249-260.
[16] M. Ouf, M. Issa, P. Merkel, Analysis of real-time electricity consumption in Canadian school buildings, Energy and Buildings, 128 (2016) 530-539.
[17] C. Rösch, T. Kohajda, S. Röder, M.v. Bergen, U. Schlink, Relationship between sources and patterns of VOCs in indoor air, Atmospheric Pollution Research, 5 (2014) 129-137.
[18] M. Hastak, C. Koo, Theory of an Intelligent Planning Unit for the Complex Built Environment, Journal of Management in Engineering, 33 (2017).
[19] M. Hastak, C. Koo, A Conceptual Framework for an Intelligent Planning Unit for the Complex Built Environment, Procedia Engineering, 161 (2016) 269-274.
[20] C. Koo, A carbon integrated management system for monitoring, diagnosing, and retrofitting the dynamic energy performance of existing buildings in a city, an urban organism, in, Doctoral Thesis. Seoul: Yonsei University, 2014.
[21] The Government of the Hong Kong Special Administrative Region Indoor Air Quality Management Group, Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places, in, 2003.
[22] An, D. Yan, T. Hong, Clustering and statistical analyses of air-conditioning intensity and use patterns in residential buildings, Energy and Buildings 174 (2018) 214-227.
[23] A. Ozawa, R. Furusato, Y. Yoshida, Determining the relationship between a household's lifestyle and its electricity consumption in Japan by analyzing measured electric load profiles, Energy and Buildings 119 (2016) 200-210.
[24] C. Miller, Z. Nagy, A. Schlueter, A review of unsupervised statistical learning and visual analytics techniques applied to performance analysis of non-residential buildings, Renewable and Sustainable Energy Reviews 81 (2018) 1365-1377.