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# Hệ thống cơ sở hạ tầng mạng cho các ứng dụng tòa nhà thông minh hướng tới tiện nghi người dùng và tiết kiếm năng lượng
# Cyber-physical Infrastructure for Smart Building Applications towards Human Comfort and Energy Savings

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## Abstract

Rapid development of information technologies facilitates modern buildings to be smarter. The smart buildings are expected to operate more efficiently to serve the occupants well. Cyber-physical systems are the key enablers for these objectives. They include various sensors and actuators, edge computing devices, human-machine interface, data analysis services to assist building operators in monitoring and decision-making. In this paper, we present such a cyber-physical system integration which has been developed and deployed in an office space. It is capable of acquiring environmental conditions of the occupants, their personal energy consumption, human interaction with the system, etc. Correlations of these information are analyzed before making any decision on adjusting the building operation. A few cases of data analyses are presented to provide the understanding of the system behaviour.

***Keywords**: Cyber-physical System, Wireless Sensor and Actuator Networks, Human Comfort, Energy Savings*

## Tóm tắt

Sự phát triển nhanh chóng của công nghệ thông tin đã giúp cho các tòa nhà hiện đại trở nên thông minh hơn. Các tòa nhà thông minh được mong đợi sẽ hoạt động hiệu quả hơn để phục vụ người sử dụng. Hệ thống hạ tầng mạng là chìa khóa chính để phục vụ mục tiêu này. Hệ thống này bao gồm rất nhiều cảm biến và thiết bị chấp hành, các thiết bị điện toán biên, giao diện người-máy, các dịch vụ phân tích dữ liệu để trợ giúp cho người vận hành tòa nhà theo dõi và ra quyết định. Trong bài báo này, chúng tôi trình bày một hệ thống như vậy đã được phát triển và tích hợp trong một không gian văn phòng. Hệ thống có thể thu thập dữ liệu môi trường quanh người dùng, năng lượng tiêu thụ của mỗi cá nhân, tương tác giữa người dùng và hệ thống, v.v… Sự liên hệ giữa các thông tin này được phân tích trước khi đưa ra quyết định thay đổi chế độ vận hành. Một số các kết quả phân tích được trình bày để cung cấp cái nhìn rõ hơn về hoạt động của hệ thống tòa nhà.

## 1. Introduction

Rapid development of information and energy technologies enable buildings to be equipped with thousands of smart devices. However, solely deployment of smart devices into a building does not make the building smart, especially if it does not satisfy the occupants' need and comfort. "In the smart building, occupants are thrown into a world of buttons and features, or one of automation and no control; there is no opportunity to create an attachment with the technology. By simplifying, perfecting, and starting over with the user in mind, the smart building can become the technological extension occupants actually desire" [1]. New management schemes for the building not only require the information within the buildings but also from outside, such as weather forecasting to plan the indoor environment adjustments in advance. Another useful information would be the time-varying energy prices. In some places, electricity market provides more options for households and businesses to buy electricity from a retailer with the best price plan as required [2][3]. The information from external sources gives an opportunity to change the behaviour of building users on energy usage, but the complexity of the building management system is also increased to achieve optimal solutions.

In this work, system integration of different sub-systems has been implemented. It includes wireless sensor networks (WSNs) for environmental monitoring, actuator networks to enable personal fans control as well as collecting user preferences, power meter connection, and data analysis services. The motivation for this work and the overview of the developed system are described in Section 2. The system design and development details are described in Section 3. Data analysis of the collected information during the system operation are reported and discussed in Section 4. Finally, the paper is concluded in Section 5 with certain directions for the future works.

## 2. Background

The emergence of wireless sensor and actuator networks and IoT devices [4] allows devices in the buildings to be connected with each other and users easily. Such systems require

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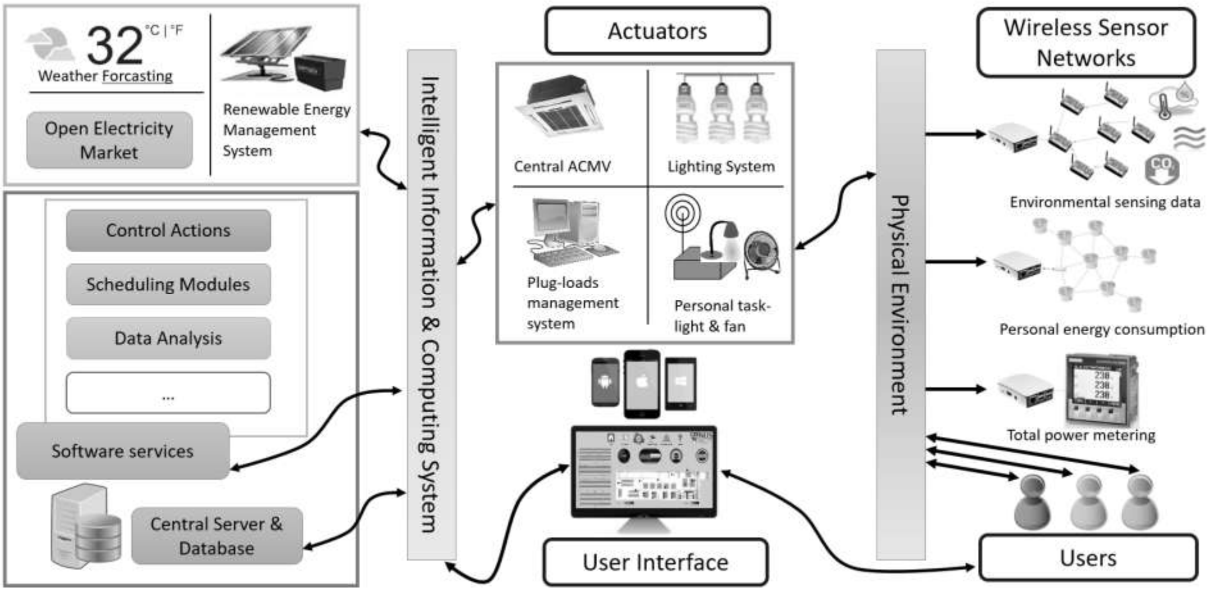


**Fig. 1. Cyber-physical system architecture with various sub-system and services**

different levels of integration like cross-technology integration of smart devices from different suppliers, cross-organization integration of information and services from different enterprises and cross domain integration of business ecosystems from different industries [5].

In smart building applications, there have been several prior efforts in estimating and achieving energy savings within the building subsystems, but in silos. For instance, a few lighting control strategies are tested in [6] including daylighting dimming control, on/off control by occupancy detection, and a combined lighting control strategy of background dimming lighting with task lighting. But the practicality of how users are given control of their personalized environment is not considered by the automation. In [7], an optimization problem of coordinating ACMV and fans to minimize the energy cost is solved, but the personal fan settings are determined through optimization rather than introducing real-time user control of personalized comfort.

It is already known that user preferences and interactions are hardly taken into account in conventional buildings comfort services, i.e. air-conditioning and mechanical ventilation (ACMV), lighting system, plug-loads. But a blind automation can result in occupant dissatisfaction and the building could also consume more energy than that which is required for the occupants. With ubiquitous computing, the paradigm in building automation is shifting towards personalised and localised comfort, in which comfort is provided only when and where it is required and as preferred, thereby also optimising the energy consumption further. In recent works [8][9], occupant feedbacks through mobile applications have been utilized to collect information regarding occupant response on their ambient environment. The data can be used to form personal comfort profiles and subsequently provided to the control systems for respective set-point scheduling to minimize the total discomfort.

Our previous work has introduced a specific wireless sensor and actuator network framework for personal thermal comfort using table fans [10]. In this work, that sub-system is being leveraged along with the integration of multiple sub-systems and services. The cyber-physical system architecture with various devices and user interface is shown in Fig. 1. This system includes multiple layers from the physical environment to digital world. The information of physical environment does not consist of only sensing parameters but also humans interacting with the sub-systems. At higher level, all the data are digitized, analysed, stored and exchanged with different components of the system. It is also open to the external data sources or system such as weather conditions or systems like renewable energy or power grid. This architecture aims to facilitate digitalized management of energy and comfort with respect to modern buildings and their indoor environment.

## 3. System Description

### 3.1. Hardware Platforms

As shown in Fig. 1, there are various devices used in our system. Each type of devices may utilize different types of communication protocols supported by different hardware and software platform. For example, a personal thermal comfort device consists of a table DC fan, Arduino node as main computing unit, a ZigBee module performing communication task and a motor driver to actuate the fan [10]. The device is also equipped with a PIR (Passive infrared) sensor for motion detection of the user.

Meanwhile, environmental monitoring is performed by using a TinyOS based wireless sensor network with Iris platform from MEMSIC. Each node has a MTS400 sensor board which includes temperature, humidity, and illuminance sensors. In order to acquire CO2 concentration, another Zigbee-based Arduino node is used to interface with K30 CO2 sensor module.

Plug-loads form another sub-system of interest. Plug-load management is not yet considered carefully in the conventional BMS and one reason would be its highly dependence on user habit. The percentage of total building energy use from plug and process loads (PPLs) which are energy loads that are not related to general lighting and ACMV is increasing, accounting for 33% of U.S. commercial building electricity consumption [11]. Thus, it would be useful to monitor the plug-loads and understand occupancy profiles to explore the strategy of reduction in PPLs energy usage. In this system, Plugwise power meters are installed at each working desk to measure the typical loads in the office like personal computer and monitor. The Plugwise module uses a secured Zigbee as communication protocol and is capable of providing the load power consumption. The module can also act as a controller to turn on and off the connected load upon request. This feature enables the system to schedule load operation or turn off unused one, and thus high energy efficiency and savings can be achieved.

In overall, Siemens SENTRON PAC3200 power monitoring meters are used for measuring the energy consumption of the whole system, especially focusing the two 3-phase split-type aircons installed in the office as these are the major loads. The meter supports Modbus TCP as one of its communication protocols with a third-party device. Beside power and energy measurements, it records rich information of the eletrical system including rms values of voltages, currents, power factor, total harmonic distortion.

As many communication protocols are used by different networks, a gateway for each network is required to be employed as intermediate device interfacing with the control central server. Furthermore, a sensor network consisting of large number of nodes are divided into sub-network to reduce the traffic loads and ensure the quality of services. A Linux-based single board computer (SBC) such as Rapsberry Pi or BeagleBone is a good candidate for this application for its small size, low power, and low cost compared to a normal laptop or desktop personal computer (PC). In this application, multiple Raspberry Pi SBCs equipped with appropriate communication module are deployed for gathering data of different sensor newtorks before forwarding to the central server.

### 3.2. Software Development and System Deployment

A few software packages have been developed for each level of the system. The software system consists of modules at different levels: sensor and actuator node, base station or gateway and control central server. Each individual sensor-actuator node performs sensing, actuating and communication tasks as the features are available. Sensing task in which the node acquires sensing values is performed periodically. Depending on the supporting features of each platform, the data is transmitted to the base station automatically or upon request. For example, most of the environmental information can be sent as soon as it is collected but the respected base station needs to send a request message to achieve the energy data from PAC3200 power meter or the Plugwise devices. Besides, the actuation task of the node if available is performed by taking input from users or control central server. Actuating information is also exchanged with the gateway depending on the mode of operation [10].

At the base station or gateway level, a Java application is developed and executed in order to communicate with all the sensor and actuator nodes in the same network. The base station application is capable of storing all the data collected from the nodes locally, performing some sort of data pre-processing, decision making regarding the control action as well as communicating with a central server of the buildings.

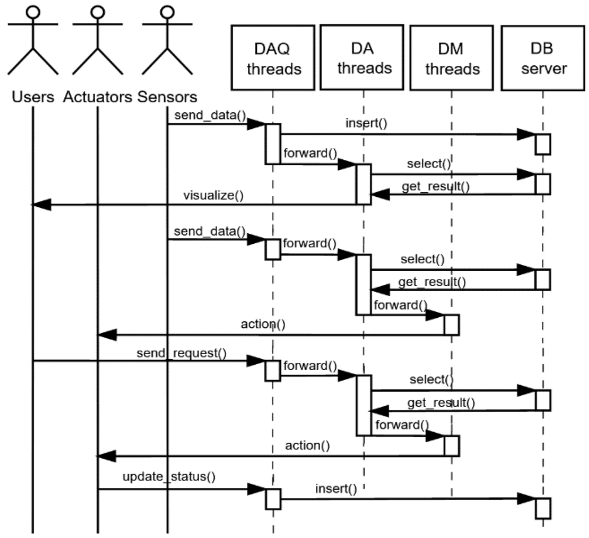
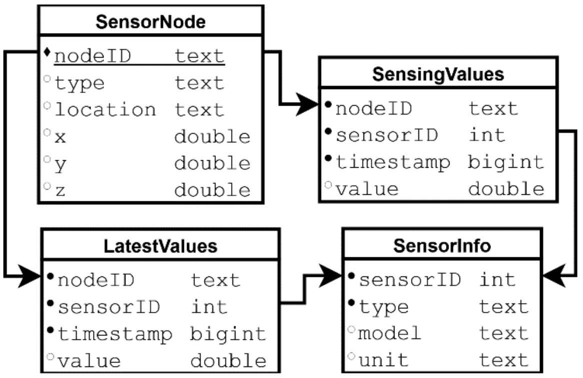


**Fig. 2. Multiple threads of the main applications**

At the control central, a multi-threading application is run to deal with data stream from different base stations. Each thread collects the data, process it and fetch into MySQL database. Besides, there are separate threads which analyse data further and make decision on the control action if necessary, as in the case of the personal fan control. Fig. 2 shows a few operation schemes of the multiple threads in the main application at control central. Input data can be provided by sensors or users to the data acquisition (DAQ) and data analysis (DA) threads. The data is then either inserted into database (DB) or further processed by decision making (DM) threads for subsequent tasks such as storing, visualization or request actuator devices to take certain actions.



| SensorNode | |
|---|---|
| ♦nodeID | text |
| ○type | text |
| ○location | text |
| ○x | double |
| ○y | double |
| ○z | double |

| SensingValues | |
|---|---|
| •nodeID | text |
| •sensorID | int |
| •timestamp | bigint |
| ○value | double |

| LatestValues | |
|---|---|
| •nodeID | text |
| •sensorID | int |
| •timestamp | bigint |
| ○value | double |

| SensorInfo | |
|---|---|
| •sensorID | int |
| •type | text |
| ○model | text |
| ○unit | text |

**Fig. 3. Database Schema for storing collected values**

The database is structured as illustrated in Fig. 3. Schema for each type of sensor networks includes SensingValues table storing the values acquired by the respected sensors and metadata tables. As multiple platforms are integrated into the system, data collected by each platform with its own sensors are organized into a sensing value table. Besides, a snapshot of all the latest values acquired by each sensor is stored in LatestValues table. It facilitates quick access of real-time or near values of all the sensors for visualization and providing an overview of the monitoring site. The metadata relates to sensor information, i.e., sensor identification number (ID), name of the sensor, model number, engineering unit, as well as the node information which is node ID, platform type, and location including the node's coordinates inside the interested area.

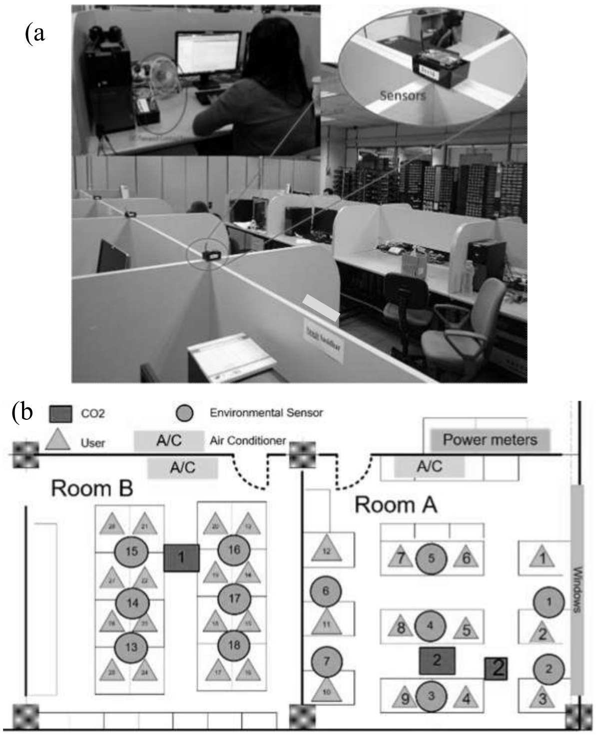


**Fig. 4 Device deployments in a shared office area: a) Actual office area, b) Deployment layout**

The whole system has been deployed in two rooms of a shared office area as shown in Fig. 4. The dimension of Room A is around 8×8 $m^2$, and that of Room B is almost the same. Room A has windows towards the west and receives direct sunlight in the afternoon. Room B is without windows that face the outdoors. Both Room A and Room B are supplied by split-type air-conditioning systems. The environmental monitoring WSN is distributed on the wall between two cubicles, i.e. each sensor node is within 0.8 – 1.5 m away from the user which is close enough to reflect the ambient temperature around him, and at the same time the sensor can avoid the direct heat of the computer cooling fan. Meanwhile a set of a personal fan and its controller is provided and placed on each user's desk. As mentioned in [10], the air speed of these table fans when being turned on can vary between 0.2m/s to 1.2m/s and in the range of 0.4 to 0.6 meter away from the user, and thus it would be sufficient to compensate the thermal comfort when the temperature increased. The Plugwise power meters are also connected in between the power sockets and the plug-loads which are personal computers and monitors. The Siemens SENTRON PAC3200 power meters are installed outside at the distribution box.

## 4. Data Analysis and Discussion

### 4.1. Data collection and other considerations

This section presents a few analyses by the control central server on the data observed by the power metering and environmental monitoring WSN. The aircon systems are metered and the power consumption is monitored every minute. The split-type unit has one outdoor unit which is the compressor and another indoor unit which has the fan.

The rating of the two aircon systems is 3.5 kW. When the outdoor unit (compressor) is on, it consumes around 3.5 kW. When only the indoor unit (fan) is on, it consumes around 90-100 W. The power measured by Siemens PAC3200 includes the power consumption of both compressor and indoor unit. The aircon on/off status is estimated from the power consumption values empirically.

The indoor temperature and relative humidity are monitored by wireless sensors placed near the user's seating area (amounts to 3-4 sensors per room) every 2 minutes. The outdoor temperature, relative humidity, rainfall and weather forecast data are obtained from the API provided by the National Environment Agency (NEA) Singapore every 5 minutes. Local weather stations are deployed for backup which gives reading every hour.

To account for occupancy, only hours between 10am to 7 pm and weekdays data are considered. This may not be completely representative of the testbed space which is a laboratory office and hence has flexible working hours, nonetheless this is reasonable for the current analysis. Room A has an approximate occupancy between 6-9 users and Room B between 12-16 users during the data collection phase for around six months. Typical time-series data of the aircon power consumption as well as indoor and outdoor temperature acquired by the system on a working day is illustrated in Fig. 5.

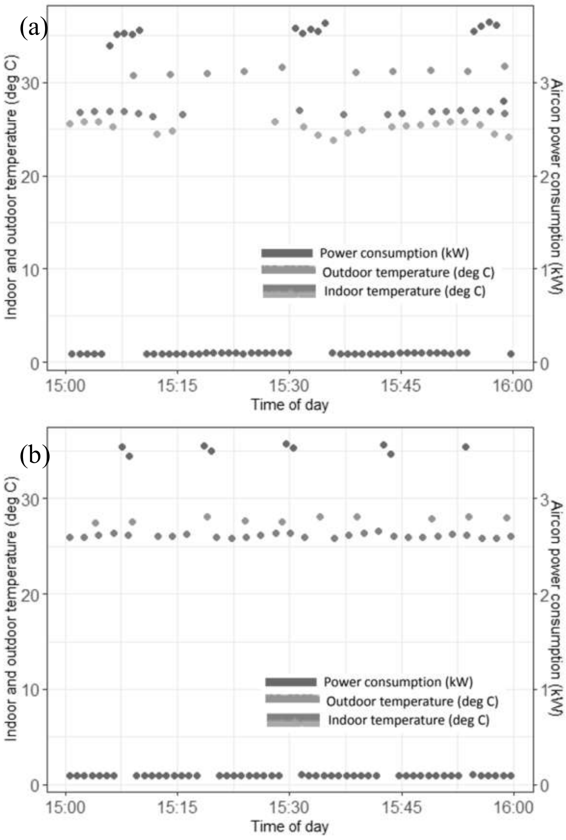


**Fig. 5. Time-series data of air-conditioning power consumption and ambient temperature acquired by the WSNs for a) Room A and b) Room B.**

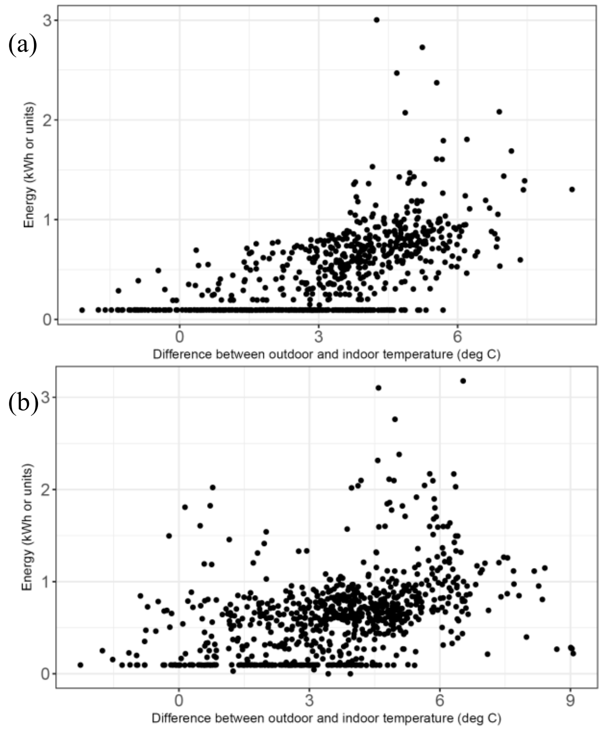


**Fig. 6. Hourly energy consumption with respect to outdoor-indoor temperature difference in a) Room A and b) Room B**

## 4.2. Energy consumption with respect to outdoor-indoor temperature difference

The hourly and daily energy consumption are computed from the data recorded along with the average of indoor temperature and outdoor temperature for the respective time periods.

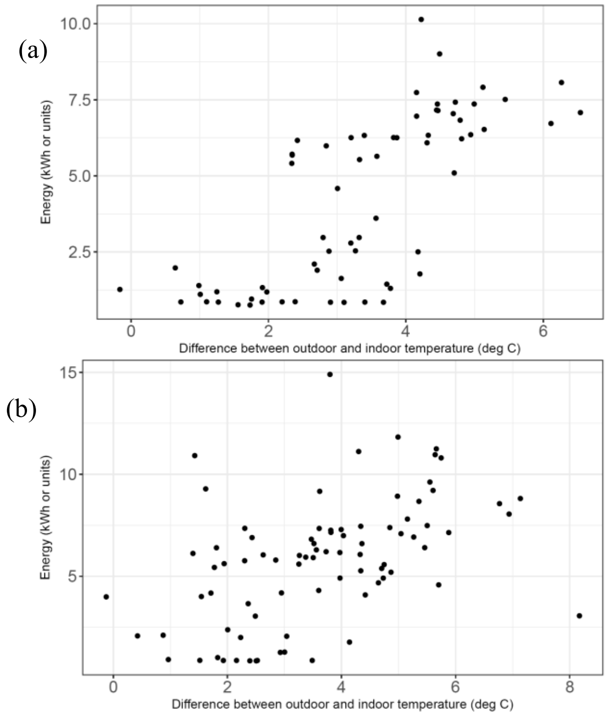


**Fig. 7. Daily energy consumption w.r.t outdoor-indoor temperature difference of (a) Room A (b) Room B**

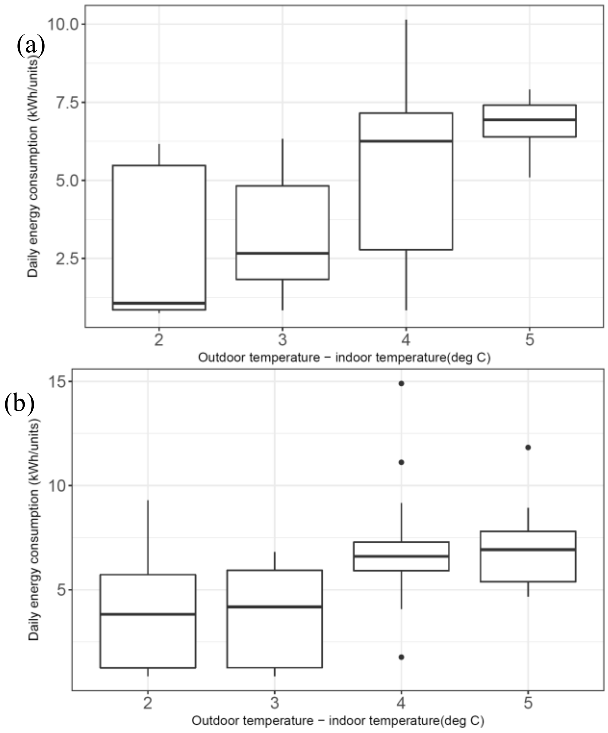


**Fig. 8. Boxplot of daily energy consumption for temperature difference 2 – 5 °C of (a) Room A (b) Room B**

The average of all sensor readings in each room is computed for the indoor temperature values. Fig. 6 shows the hourly energy consumption considering only the occupied hours for both rooms. A trend can be noted where there are higher energy consumption values for higher temperature difference. This trend can be also seen in the daily energy consumption plots for the two rooms shown in Fig. 7. Fig. 8 presents the boxplot of daily air-conditioning energy consumption compared for temperature difference between 2 to 5 °C (these values have sufficient data available, more than 10 days each). The lower energy consumption for 2 – 3 °C temperature difference as compared to 4 – 5 °C can be noted from this figure. The mean, median and standard deviation of the daily energy consumption for different values of difference between outdoor and indoor temperature along with the number of days available for the computation of these metrics are summarized in Table 1. The average daily energy consumption for a temperature difference of 2 – 3 °C was 3.32 kWh and for a temperature difference of 4 – 5 °C was 6.51 kWh.

**Table 1. Daily energy consumption**

| | Diff[1] | Days[2] | Mean[3] | Median[4] | STD[5] |
|---|---|---|---|---|---|
| Room A | 2 | 12 | 2.54 | 1.07 | 2.37 |
| | 3 | 16 | 3.16 | 2.66 | 1.96 |
| | 4 | 18 | 5.42 | 6.25 | 2.81 |
| | 5 | 10 | 6.83 | 6.93 | 0.82 |
| Room B | 2 | 18 | 3.91 | 3.83 | 2.62 |
| | 3 | 13 | 3.66 | 4.18 | 2.46 |
| | 4 | 21 | 6.80 | 6.60 | 2.63 |
| | 5 | 13 | 6.98 | 6.92 | 2.01 |

[1] Difference between outdoor and indoor temperature (°C)
[2] Number of days available for computation
[3] Mean of daily energy consumption (kWh)
[4] Median of daily energy consumption (kWh)
[5] Standard deviation of daily energy consumption (kWh)

The information in Table 1 would then help the building operator to make the decision rule for the control system to increase the indoor temperature and thus reduce the difference between the indoor and outdoor ones to save more energy. In order to maintain the thermal comfort, the personal fan at each table would be then adjusted automatically by the central system or by the users themselves. Fig. 9 illustrates the fan usage pattern by multiple users when the set point temperature is changed on different days.

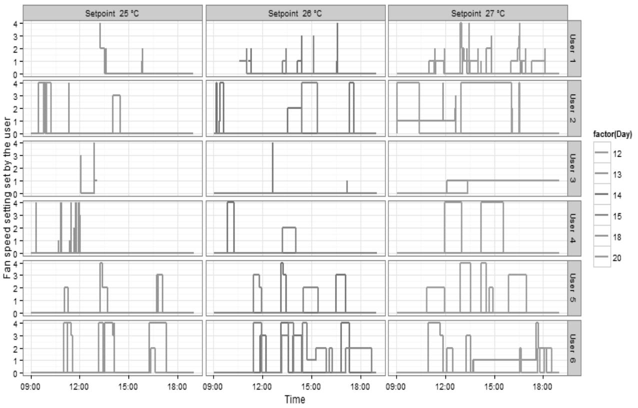


**Fig. 9. Fan usage data for the experiment period**

As represented in Fig 10, a savings of 32.1% was possible in Room-B of office space for 3°C increase in temperature setpoint of the ACMV, while being compensated by personal fan control. In an existing work based on EnergyPlus simulation of an office space [12], nearly 17% savings was possible [13] through the scheduling of ACMV and fans. The system in our study could achieve higher savings by keeping the ACMV setpoint uncontrolled while giving the users personalized control of their own fans.

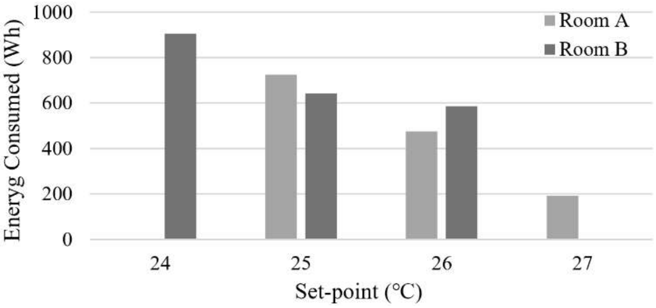


**Fig. 10. ACMV energy consumption at different set-points in the two room**

## 5. Conclusion

In this work, a cyber-physical system for smart building has been presented. Data collection and analysis of energy usage for the air conditioning system are performed. The data are correlated with the indoor and outdoor environmental conditions. The correlations are meant for the control system for planning control action subsequently with the expectation of saving more energy. This work has this established a practical cyber-physical platform on which coupled objectives of human comfort and energy efficiency can be combined. Many scopes can be extended for future works such as new control strategies when considering the information of user presence/localization, and scheduling the load operation based on time-varying electricity prices from open market is available. Future work would also investigate the quantitative comparison of energy savings achievable with respect to other research works, using the cyber-physical system presented.

## Acknowledgement

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