Simulation of Local Climate Control in Shared Offices Based on Occupants Locations and Preferences

Zheng Liu

A thesis
In the Department of
Building, Civil, and Environmental Engineering

Presented in Fulfillment of the Requirements
For the Degree of Master of Applied Science (Building Engineering) at
Concordia University
Montreal, Quebec, Canada

August 2017

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Zheng Liu

Entitled: **Simulation of Local Climate Control in Shared Offices Based on Occupants Locations and Preferences**

And submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining committee:

______________________________________ Chair

______________________________________ Examiner

______________________________________ Examiner

______________________________________ Supervisor

Approved by ______________________________________

Chair of Departmental or Graduate Program Director

____

Dean of Faculty

Date ______________________________________

ABSTRACT

Simulation of Local Climate Control in Shared Offices Based on Occupants Locations and Preferences

Zheng Liu

It is estimated that building energy consumption (BEC) accounts for one-third of the total global energy consumption, and Heating, Cooling, and Air-conditioning (HVAC) accounts for almost half of the energy consumption of buildings. To efficiently achieve more energy saving from the HVAC systems, narrowing the gap between the actual energy consumed and the demanded heating and cooling loads is found to be a promising strategy. Therefore, occupancy-driven HVAC management is attracting great attention. On the other hand, future smart buildings will have the ability to detect and locate the occupants, and adjust the HVAC system accordingly, which is expected to result in considerable energy savings. This research proposes a local climate control strategy in open space, such as shared offices, by dividing the space into zones according to the number of HVAC terminal units and adjusting the operation of each terminal unit based on occupants' preferences and presence in the zone. To evaluate the performance regarding energy consumption and occupancy thermal comfort, and the feasibility of the proposed local climate control, three case studies are implemented. The occupancy presence pattern is captured by a Bluetooth Low Energy (BLE)-based tracking system. Based on a four-week test carried out in a graduate laboratory in Concordia University, the occupancy profiles and different HVAC operation scenarios are created as the inputs of the building energy simulation. The simulation is run for three months for cooling and the results show that, with the adoption of the proposed local climate control strategy, 15% or 36% of the energy consumption can be saved compared with applying a dynamic schedule using a motion detector or a fixed schedule, respectively. In addition, the occupants' comfort level can be increased by an average of 6%. In addition, sensitivity analysis is conducted with respect to the factors affecting the effectiveness of the proposed climate control strategy and the HVAC setpoint temperature. It is concluded that the proposed local climate control strategy is effective in reducing the energy consumption and improving occupancy thermal comfort, however, the extent of the effectiveness depends on factors of building properties, occupancy attributes, and HVAC operation.

ACKNOWLEDGEMENT

I would like to betoken my immense gratitude to my supervisor, Dr. Amin Hammad, without whom I would not be able to complete my Master degree. During this research, his wisdom and guidance always inspired me with new ideas; his support and patience always helped me overcome the challenges.

I would like to thank my parents for their firm support. They always place invaluable faith in me when I lose confidence and doubt myself, and gave me so much love and strength through my surgery. I also express my sincere gratitude to my cousin Yue and her husband Mingkang, who take great care of me, and their daughter Catherine, always being our pride and joy.

Thanks also to my dear colleagues, Ms. Shide Salimi, Ms. Negar Salimzadeh, Ms. Neshat Boloorian, Mr. Alhusain Taher and Mr. Amir Housain Sharif for their participation and cooperation in the tests.

Finally, special thanks to my beloved friend MASC Baoguang Xu for his great help in the MatLab program and for his consideration and encouragement when I'm writing this thesis.

DEDICATION

I would like to dedicate this thesis to my family for their all-enduring and selfless love.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
AoA	Angle of Arrival
AoI	Area of Interest
BAS	Building Automation System
BEC	Building Energy Consumption
BEMSs	Building Energy Management Systems
BLE	Bluetooth Low Energy
CAD	Computer-Aided Design
CAGR	Compound Annual Growth Rate
CBECS	Commercial Building Energy Consumption Survey
CFD	Computational Fluid Dynamics
CSV	Comma-Separated Values
DDC	Direct Digital Control
DFL	Device Free Localization
ECG	Electrocardiogram
GPS	Global Positioning System
HCI	Host Controller Interface
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz
IC	Influence Coefficient
ID	Identification
IES<VE>	Integrated Environmental Solutions <Virtual Environment>
IPS	Indoor Positioning System
KW	Kilo Watt

KWh	Kilo Watt Hour
LBS	Location Based Services
Li-Fi	Light-Fidelity
MRM	Mobile Resources Management
PC	Personal Computer
PIR	Passive Infrared
PoE	Power-over-Ethernet
PV	Physical Value
QCP	Quuppa Customer Portal
QDP	Quuppa Data Player
QPE	Quuppa Positioning Engine
QSP	Quuppa Site Planner
RFID	Radio-Frequency Identification
RMD	Received Message Data
RSS	Received Signal Strength
RToF	Real Time of Flight
SIG	Special Interest Group
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UWB RTLSs	Ultra-Wideband Real-Time Location Systems
VAV	Variable-Air-Volume
VLC	Visual Light Communication
Wi-Fi	Wireless-Fidelity

CHAPTER 1 Introduction

1.1 General Information

The Heating, Ventilation and Air Conditioning (HVAC) system consumes the major part of energy in buildings. By analyzing the gap between the actual energy consumed and the required energy to satisfy heating/cooling loads, it is estimated that an average of 38% of the energy can be saved with the adoption of more efficient control strategies (DOE, 2011). Occupancy-driven management strategies have attracted great attention due to the potential energy savings. Therefore, the development and implementation of these strategies are of primary importance. On the other hand, future smart buildings will have the ability to detect and locate the occupants, and adjust the HVAC system to better satisfy their preferences, which is expected to result in considerable energy savings. This thesis aims to utilize an occupancy tracking technology for occupancy data collection and to simulate the energy performance that can be achieved by applying local control of the HVAC system based on the locations and preferences of the occupants in an open space office with multiple zones. In the case study of this research, a Bluetooth Low Energy (BLE)-based tracking system is used to collect the occupancy data and energy simulation software DesignBuilder is used to model one office at Concordia University and simulate its energy consumption.

1.2 Research Objectives

This research aims to achieve the following objectives: (1) Investigating the occupancy tracking system Bluetooth Low Energy (BLE) and developing a data processing method to obtain the occupancy profile; (2) Proposing a local climate control in shared offices based on occupants' locations and preferences and evaluating the energy saving of the proposed strategy based on building energy simulation results; (3) Investigating the factors affecting the energy consumption of the proposed strategy and conducting the sensitivity of the HVAC setpoint temperature.

1.3 Thesis Organization

This research is structured as follows:

Chapter 1 *Introduction*: this chapter introduces the research topic and objectives, and presents the structure of the thesis.

Chapter 2 *Literature Review*: this chapter reviews the existing literature on the impact of occupant-related factors on the energy consumption of buildings and the occupant-positioning technologies along with their applications in various fields.

Chapter 3 *Proposed Methodology*: this chapter proposes the local control strategy. The factors involved in the energy consumption are organized. In addition, the technology selected for collecting occupants' information (i.e., BLE) and the simulation program selected for the building energy simulation (i.e., DesignBuilder) are introduced. The advancement and performance of BLE is analyzed to ensure that it is suitable to use for occupant tracking.

Chapter 4 *Implementation and Case Study*: this chapter consists of the implementation of the proposed strategy, which is presented through three case studies and the analysis of the collected data.

Chapter 5 *Conclusions and Future Works*: this chapter summarizes the present work and concludes the findings. This chapter also includes the recommendations for the BLE tracking system.

CHAPTER 2 Literature Review

2.1 Introduction

It is estimated that the world energy consumption will increase by 56% from 2010 through 2040, as shown in Figure 2-1 (SUSRIS, 2013). Due to the catastrophic climate change, growing population and shortage in fossil fuels, the imbalance of increasing energy demand and limited energy resources have become a global environmental and economic problem and a driving force for researches on energy conservation techniques (Bratt et al., 2015). Building energy consumption (BEC) accounts for one-third of the total global energy consumption (Yang and Becerik-Gerber, 2014).

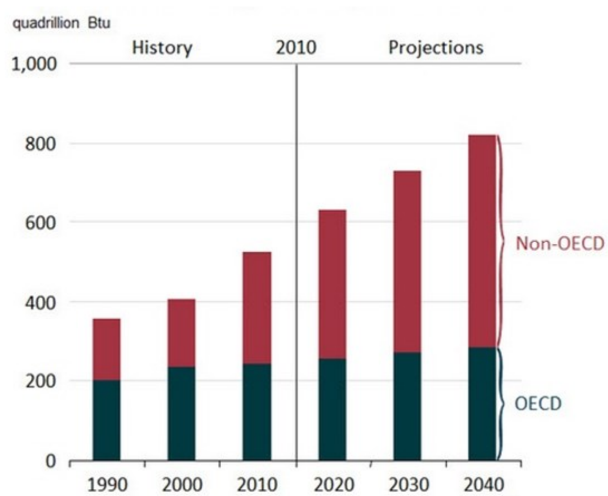


Figure 2-1 World energy consumption (SUSRIS, 2013)

Perez-Lombard et al. (2008) reviewed the energy consumption information related to buildings and particularly the HVAC systems in buildings. They found that 20% to 40% of the total energy in developed countries is consumed by buildings, and HVAC and its associated energy consumption accounts for almost half of the energy consumption of buildings. In Canada, approximately 85% of the total energy in institutional and commercial buildings is consumed by heating, cooling, lighting, and IT equipment (NRCan, 2011). It is found that with the adoption of more efficient system-control technologies, 38% of energy related to HVAC can be saved (DOE, 2011). Besides, in the life cycle of buildings, 80% of the energy is consumed in the operation phase. Therefore, the reduction in building energy consumption calls for a more efficient control to improve the operations based on actual demands.

2.2 Building Automation

Building energy management systems (BEMSs) are computer-based systems assisting in the management, control and monitoring of HVAC and lighting, energy monitoring and targeting, etc. They provide the ability to monitor the plant constantly and recall the monitored data, better communicate over the telephone from remote sites, save labors and make the maintenance and management operations more efficient (Levermore, 2000). With programmed routines and repetitive functions, relatively simple operation, quick response to complaints, improved management information and graphical representation of operating conditions, BEMSs enable up to 10% reduction in energy consumption and costs (Defence Estates, 2001).

2.3 Occupancy Behavior

Occupant behaviors refer to the interactions between occupants and the appliances in buildings, including operable windows, lights, blinds, thermostats, and plug-in appliances (Yan et al., 2015). Figure 2-2 describes the impact of occupant behavior on building energy performance. The factors influencing occupant behavior include short-term factors, such as the feelings of occupants, and long-term factors, such as the principles or habits of occupants (Yan and Hong, 2014).

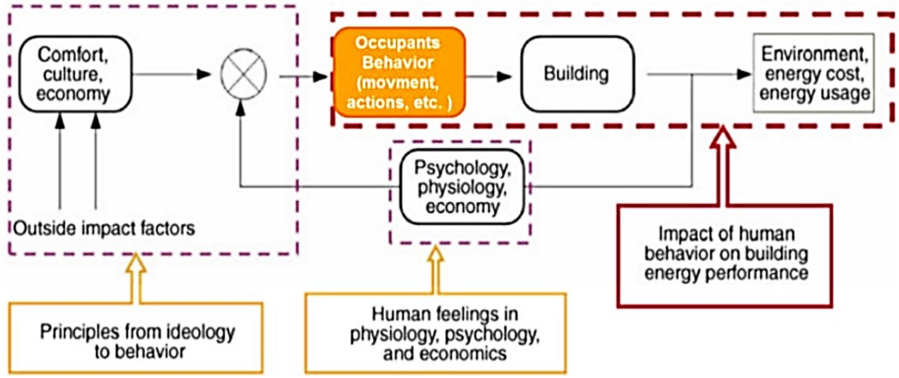


Figure 2-2 Relationship of occupant behavior and building energy performance (Yan and Hong, 2014)

In the EBC Annex 53 project summary report (2016), the driving factors of energy use in buildings are identified as: (1) climate, (2) building envelope, (3) building energy and services systems, (4) indoor design criteria, (5) building operation and maintenance, and (6) occupant behavior. In comparison with the great progress made in the first five factors, occupant behavior in buildings has not been well defined and modeled in previous studies, which leads to significant uncertainty in predicting the building energy performance. Therefore, large discrepancies can be demonstrated in buildings with similar functions and locations. For example, as Figure 2-3 shows, comparing the measured and designed Energy Use Intensity of 62 Leadership in Energy and Environmental Design (LEED) buildings in the United States, the normalized root-mean-square error is 18% (Turner and Frankel, 2008).

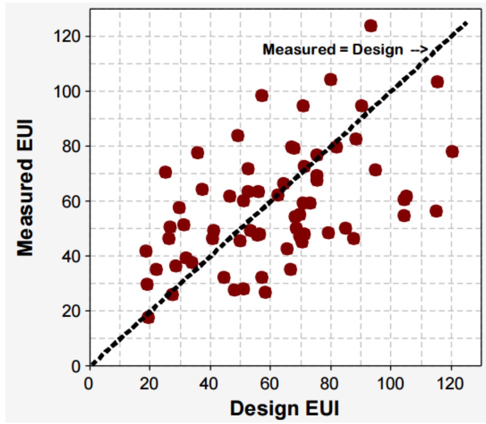


Figure 2-3 Comparison between measured and designed Energy Use Intensity (EUI, in kBtu/sf) of 62 LEED new construction buildings (Turner and Frankel, 2008)

2.4 Occupancy-Related Parameters Analysis and Energy saving

Occupant behavior affects HVAC energy consumption with respect of the thermal loads, ventilation loads, and conditioning requirements of HVAC control settings to meet their thermal comfort and standard air quality (Yang and Becerik-Gerber, 2014).

Duong (2016) analyzed five case studies of academic buildings to illustrate the potential energy saving regarding lights, HVAC and plug load with the application of occupancy modelling and occupancy sensors and also put forward the challenges caused by the diversity and variability in occupancy and activities in campus. In the case studies, the energy usage and occupancy data of the buildings are collected using metering devices and cameras. The strategy adopted for the prediction of energy consumption is black box (data driven approach), white box (physics driven approach) and grey box (hybrid of black box and white box). The black box model needs to collect a large amount of data to create occupancy schedules and the white box model predicts the energy usage through energy simulation; with the combination of both, the grey box model, can reduce the errors between the predicted and measured values. It is concluded that to reduce the energy usage in academic buildings, the creation of occupancy schedule and the education of the occupants on the energy-saving awareness are of great importance. Besides, a standard procedure to improve the energy saving is proposed, including re-lamping (LED lights), direct digital controls (DDC), implementation of Building Automation System (BAS), the black and white box models and grey box model.

A report for U.S. Department of Energy proposes three cases to identify the energy savings using occupancy-based control in variable-air-volume (VAV) systems of large offices. The result shows that 17-23% of energy in HVAC and lighting can be saved by using advanced occupancy sensors (Zhang et al., 2013). For individual offices, a group of researchers used synergy occupancy sensor nodes to detect occupancy and implemented the presence system in simulation. They found that the daily HVAC savings can reach 10-15% after applying the occupancy system (Agarwal et al., 2010). Hong and Lin (2013) simulated three work styles (austerity, standard and wasteful) of occupants to quantify the impact of occupants' behavior in individual offices. They defined the occupancy-related parameters (temperature set points for cooling and heating, HVAC operation time, light control after leaving, daylighting control, etc.) for each work style. For example, occupants in austerity work style turn on the HVAC system one hour late after they arrive and turn it off one hour before they leave, adjust the light in three steps dimming according to the daylight condition, and turn off lights and HVAC system when they leave the offices. It is concluded that the austerity work style can save up to 50% of the source energy. Energy savings of various lighting and blind control systems were obtained by defining four types of user behavior in office buildings (Parys, 2009). The simulation results showed 10% reduction of the energy consumption by improved behavior on the daylight dimming system.

To quantify the energy savings potentials by improving the occupancy-related parameters, Azar and Menassa (2012) conducted sensitivity analysis on eight parameters in two climate zones. In addition, they developed a comprehensive framework to integrate existing database, energy modeling and parametric variation (2014). They modeled a typical administrative/professional building with the characteristics averaging the data from Commercial Building Energy Consumption Survey (CBECS) as base case. Then they varied eight occupancy-related parameters (temperature set point for cooling and for heating when the building is occupied and unoccupied, building schedule, after-hour lighting use, after-hour equipment use, hot water consumption) in a certain range based on CBECS and ASHRAE standards and compared with the result in the base case. By calculating sensitivity influence coefficients (IC), the sensitivity of the simulated model to the parameters can be measured and it helps define the most and least influential operations. To generalize their study, a framework with three phases (data gathering and stock aggregation, energy modeling and back casting, parametric variation) was then developed to provide directive significance for the decision-makers to improve the energy performance. They followed the framework, simulated 96 buildings with the combination of buildings with different sizes, locations and ages in 2 cases (base case and the alternative case with improved operations in temperature set points for heating and cooling and after-hour lighting and equipment use) and presented the results of the energy consumption categorized by different systems (HVAC, Equipment and Lighting), by different sources (electricity and gas) and energy that can be saved from the actual buildings in US. Inaccuracy of their studies may result from the simplification of the input characteristics and occupancy parameters by averaging the survey data and values in ASHRAE standards, but the results are significant to energy policy making.

There are four levels of occupancy models: building level, occupancy status of space, number of occupants in a space, and the location of occupants (Feng et al., 2015). The higher level of occupancy information we can extract, the more accurate the simulation will be and the more energy the control strategy can save. To achieve occupancy-based control, common occupancy sensors are utilized to identify presence and advanced occupancy sensors are utilized to count the number of occupants in a zone and track their locations. The occupancy-tracking technologies are reviewed in Section 2.5.

2.5 Occupant-Tracking

2.5.1 Indoor Positioning System

Indoor positioning system (IPS) locates the people or objects inside buildings using mobile devices to collect sensory information, such as, radio waves, magnetic fields, acoustic signals (Curran et al., 2011). There are many technologies constructing the systems such as Ultra-Wideband (UWB) Real-Time Location Systems (RTLSs), BLE (Bluetooth Low Energy), Li-Fi (Light-Fidelity), magnetic resonance, etc., to detect and sense the occupancy information. The indoor positioning systems can be applied across various areas including health care, industrial internet, retail, security, sports, etc.

There are many researchers comparing the existing location positioning technologies in the market based on different aspects. Wagner and Timmermann (2012) organized the parameters that need to be taken into account in the comparison and created a comprehensive parameter structure, as shown in Figure 2-4.

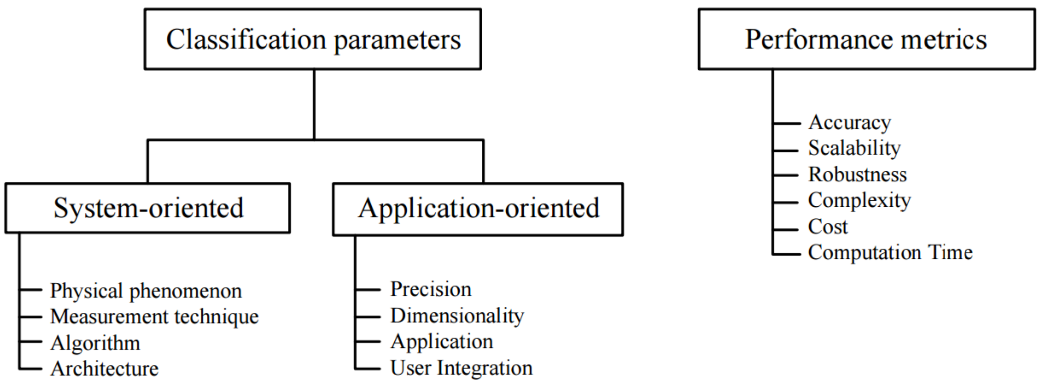


Figure 2-4 Parameter structure for comparing different location positioning technologies (Wagner and Timmermann, 2012)

To select the suitable technology for a specific case, understanding the principles of the systems is very important. Table 2-1 lists different types and sub categories of the technical specifications mentioned in the system-oriented parameters. The measurement techniques and algorithms will be explained in Sections 2.5.2 and 2.5.3, respectively.

2.5.2 Location Measurement Techniques

Caffrey and Stüber (1998) overviewed the radiolocation methods, which are signal strength, angle of arrival, time of arrival and the combination of the above, as shown in Figure 2-5. Taking the raw physical value (PV) of the sensor output for analysis, as shown in Figure 2-5 (a), is the simplest technique. Time of arrival (ToA) calculate the disctance between the sender and the receiver by multiplying the duration of the travel time, which is x as shown in Figure 2-5 (b), and the speed of the signal propagation. Received signal strength (RSS) compares the sent signal power with the received signal power to measure the distance between the sender and the receiver, as shown in Figure 2-5 (c).

Table 2-1 Summary of the technologies

Technical specifics	Sub categories	Examples
Physical phenomenon	Radio frequency	GPS, RFID, UWB, Bluetooth, Zigbee
	Light	Laser, Infrared light (visible) Videometric (invisible)
	Sound	Ultrasonic, bodysound
	Magnetic field	Magnetic sensors
	Other	Footstep pressure, load cells panel (pressure)
Measurement technique	Time of arrival (ToA)	--
	Time difference of arrival (TDoA)	--
	Angle of arrival (AoA)	--
	Received signal strength (RSS)	--
	Received message data (RMD)	--
	Real time of flight (RToF)	--
Algorithm	Triangulation	--
	Scene analysis / Fingerprinting	--
	Proximity	--
Architecture	Infrastructure-based	--
	Inertial System	--

Similar to radar, Real time of flight (RToF) measures the duration travel time from the time t_S that the signal is sent to the time t_R that the signal comes back and calculate the distance, as shown in Figure 2-5 (d). Received message data (RMD) uses the information transported by the signal other than the travel time or signal strength mentioned in other techniques, as shown in Figure 2-5 (e). It is based on origin approximation. A well-known application of origin approximation is finding the location of the caller’s mobile phone. As shown in Figure 2-5 (f), time difference of arrival (TDoA) calculates the location of the sender based on the differences of the durations of travel time measured between the sender and different receiver. Angle of arrival (AoA) uses a directional antenna to locate the sender or receiver by the direction of the signal, as shown in Figure 2-5 (g). The angle of arrival can be obtained by comparing the receiver array angle to the reference coordinate system.

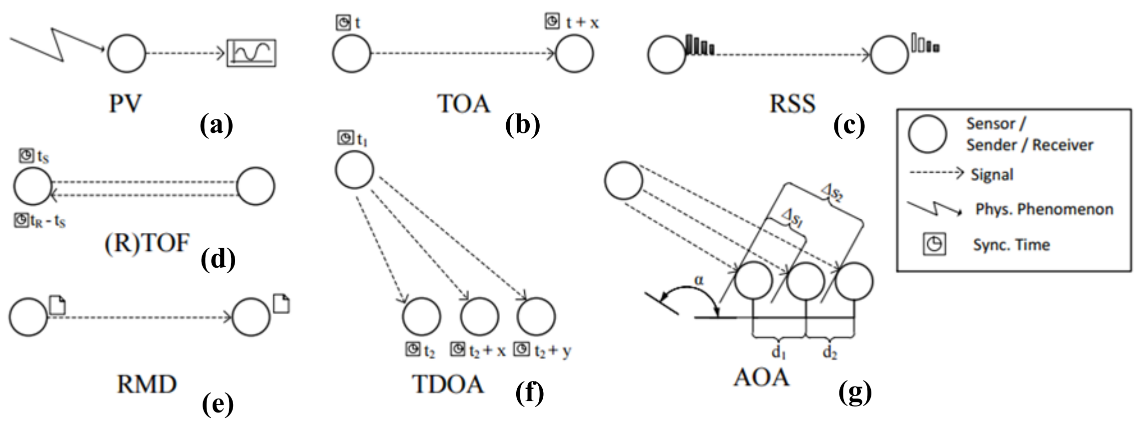
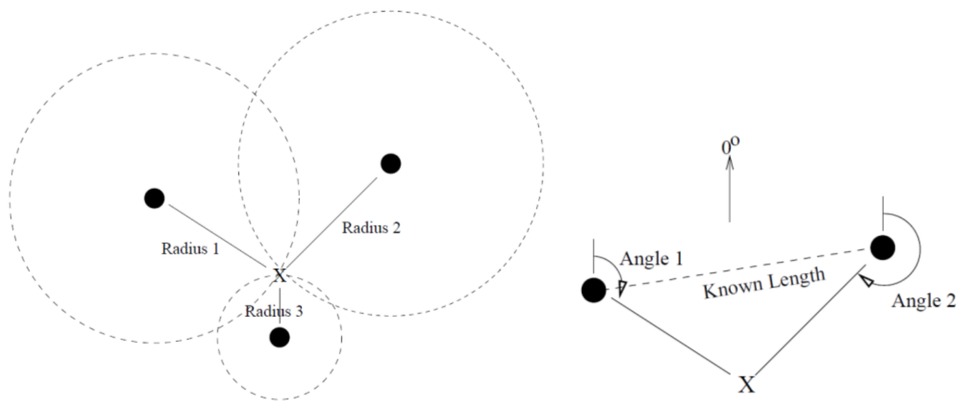


Figure 2-5 Location measurement techniques (Wagner and Timmermann, 2012)

2.5.3 Location Positioning Algorithms

Hightower and Borriello (2001) reviewed three principal location sensing algorithms, triangulation, scene analysis and proximity. Triangulation can be divided into lateration and angulation. Lateration can be explained as shown in Figure 2-6 (a), in two dimensions (2D), to obtain the position of an unknown object X, distance measurements from at least three non-collinear points (i.e., Radius 1, 2 and 3) are needed. Similarly, in three dimensions (3D), distance measurements from at least four non-coplanar are needed. As shown in Figure 2-6 (b), angulation requires at least two angles (sharing same reference vector) Angle 1 and 2, and one distance measurement in 2D to locate an unknown object X. In 3D, an azimuth measurement has to be added.



(a) Lateration **(b) Angulation**

Figure 2-6 Location positioning of object X using lateration and angulation (Hightower and Borriello, 2001)

To illustrate the mathematical principles of angulation, as can be seen in Figure 2-7, three points, two reference points N_1 (g, h) and N_2 (a, b) and the target point T (x, y) are involved. In the location positioning practice, the reference points represent the sensors with known positions and the target point refers to the object to be located.

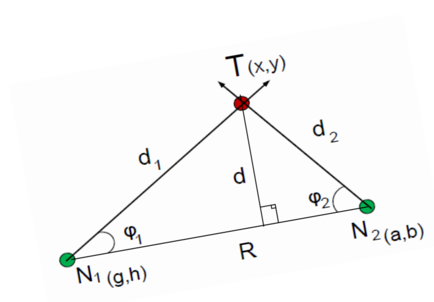


Figure 2-7 Mathematical principle of angulation (Khalel, 2010)

Knowing the coordinates of the reference points(a, b) and (g, h), d_1, d_2 and R (the lines among the reference points and the target point), d (the perpendicular line between R and the target point), and φ_1 and φ_2 (the angles between d_1 and R, d_2 and R), the coordinates of the target point (x, y) can be computed using trigonometric functions. The simplified equations are Equation 2-1 and Equation 2-2 (Khalel, 2010). From the equation, it can be concluded that the coordinates of the target point T can be calculated merely using the coordinates of the reference points and the angles between the reference points and the target point.

$$y = x \tan \varphi_2 + (b - a \tan \varphi_1) \tag{2-1}$$

$$x = \frac{b - h - a \tan \varphi_2 + g \tan \varphi_1}{\tan \varphi_1 - \tan \varphi_2} \tag{2-2}$$

Scene analysis locates the position of objects in a scene according to their features from a particular vantage point. There are two types of scene analysis, static and differential. Static scene analysis matches the features with the dataset that is predefined to acquire the position of objects; Differential scene analysis compares the differences among successive scenes observed for the movements of position. As for proximity, it is a technique that measures if the object is near to one known point or a set of known points. There are three implementations of proximity location sensing, including physical contact, being in the range of access points in wireless cellular network and the association with identification systems (Hightower and Borriello, 2001).

2.5.4 Bluetooth Low Energy (BLE) and Its Applications

The development of wireless sensing technology is in increasing demand. In 1998, Bluetooth Special Interest Group (SIG) formalized the first specification of Bluetooth, which was one of the first standardized wireless technologies and inspired the concept of wireless sensing. But the disadvantages of Bluetooth, such as, high energy consumption of transceiver ships, long latency of connection, large memory allocation due to complex protocol stack, and overhead due to large data packets, add limits to this application. To resolve these drawbacks, reduce the energy consumption and cost while maintaining the similar communication range, in 2010, Bluetooth Low Energy (or Bluetooth Smart) was launched as one of the protocols in Bluetooth Core Specification version 4.0 (Mackensen et al., 2012). The applicability of BLE in wireless sensors has been evaluated by researchers like Gomez et al. (2012), Mackensen et al. (2012), and Mikhaylov et al. (2013). The application fields of BLE cover consumer electronics, peripherals, medicine, health, sports and fitness, Industry automation, automotive, advertising and beacon sensing, etc. It is predicted that the BLE enabled devices shipments will increase from 1.8 billion units in 2014 to 8.4 billion units by 2020 with a compound annual growth rate (CAGR) of 29% (IndustryARC, 2016).

Compared with the classic Bluetooth, BLE uses much less power (can last up to three years on a single coin battery) and is 60% to 80% cheaper, although it has similar communication ranges. Therefore, BLE is ideal for running long term on power sources (Bluetooth, 2014).

Smart phones, tablets, BLE-enabled sensors and any device implementing the BLE standard can be the BLE hubs. BLE communication is composed of small packets of data called *Advertisements*, which are broadcast in one way through radio waves, at a regular interval by beacons or other BLE enabled device. The broadcast range of BLE can be up to 100 meters, which is much larger that the classic Bluetooth (10 meters), making BLE perfect for indoor location tracking and awareness. The *Advertisements* are collected by the BLE-enabled devices as mentioned before. For example, the smartphones can use the *Advertisements* in the applications to trigger messages and prompts (Ibeaconinsider, 1995).

Texas Instruments (2016) developed the first Bluetooth smart development kit focused on wireless sensor applications called SensorTag, which includes temperature sensor, humidity sensor, pressure sensor, accelerometer, gyroscope and magnetometer. To use the SensorTags for indoor positioning, the tags are also designed to support iBeacon, the name of beacon for Apple's technology standard, which allows Mobile Apps (running on both iOS and Android devices) to receive signals from beacons. As shown in Figure 2-8, users can install a mobile application to visually localize the SensorTags in the detected area, where sharing the same Major value (Maj) indicates that the SensorTags are in the same group and Minor value (Min) identifies each specific SensorTag. The battery life of the SensorTags ranges from a few months to a year depending on the time of use in beacon mode.

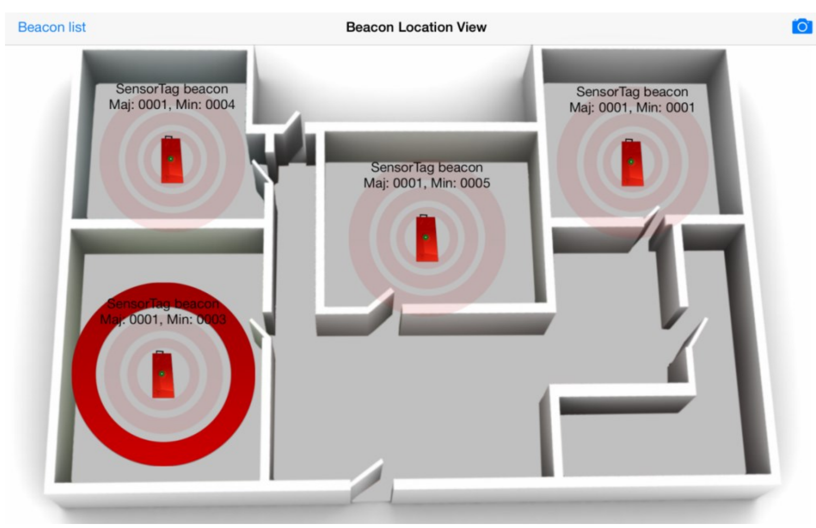


Figure 2-8 iBeacon location view (Texas Instruments, 2014)

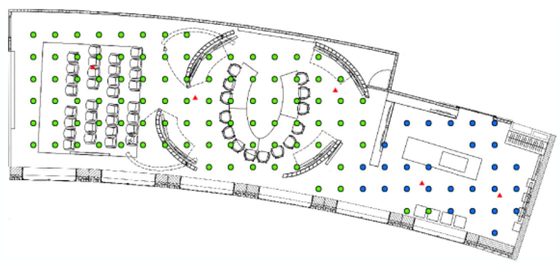
Mackensen et al. (2012) did a feasibility study on self-designed BLE-based wireless sensors to explore the characteristics of the BLE-based sensor system. They concluded that the system has lower power consumption, good data throughput, small and simple software stack and simple implementation. BLE also shows great potential in many applications. Yu et al. (2012) proposed and implemented a BLE-based wireless electrocardiogram (ECG) monitoring system prototype as a health care device. The system enabled real-time display of ECG data on smartphone platforms. The implementation showed great benefits in eliminating the constraints in hard-wire link and saving power in the long term. To detect the occupancy in smart buildings, Conte et al. (2014) developed a modification of iBeacon protocol, a BLE-based system called BLUE-SENTINEL. They validated the system in a real environment and proved the high accuracy that can be comparable with the most accurate Wi-Fi-based system by then and the low power consumption.

BLE can be also used in advanced sports analytics to improve scouting and coaching. A real-time tracking system was developed by HockeyTech (2017) partnered with Quuppa to advance the collection of player performance data in hockey games as shown in Figure 2-9. To visualize the game in real time, tags are mounted on the players and a Radio-Frequency Identification (RFID) chip is embedded in the puck. With 40 million roles of data for every game, the system is able to gather comprehensive information about the game with respect of players' travelled time, speed, travelled distance, position, puck possession and puck tracking, and was able to recreate the game.

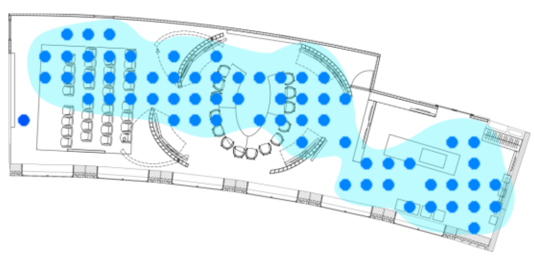
Figure 2-9 Real Time Location System used in Hockey game (HockeyTech, 2017)

Prosegur, a company that offers private security services collaborates with Quuppa Intelligent Locating System on its MRM (Mobile Resources Management) Platform called iTrack to provide real-time locating and more efficient allocation of security sources. This innovation enables to assign tasks as needed, daily (security rounds and supply deliveries) and exceptional (emergency and evacuation), to different groups of staff in real-time (Prosegur, 2015).

Ham (2015) ran three tests to investigate the performance of Quuppa indoor positioning system in an open space divided into three zones to simulate two types of rooms in a hospital (single patient's room and storage room) and develop a model for localization of a kind of hospital asset, i.e. IV pumps, using a map matching method. To assure that the performance of the indoor positioning system can meet the requirements of tracking the assets in the hospital, technical and operational performance parameters including accuracy, precision, coverage etc. are proposed and measured. According to the outcome of map matching, it is concluded that the system captured 70% correct localizations, as shown in Figure 2-10 (the proportion of the tags in (b) and the tags in (a)), and therefore, it can meet the needs for tracking the IV pumps in the hospital. It is estimated that a radial distance of 2 m can be covered with one locator and 5 m with two. However, since the tests were done in a different place as simulation, the performance can vary with the change in the AoI (area of interest) due to the ceiling height and structural elements, etc. To reach the sub-meter accuracy as much as possible, there are solutions such as denser distribution of locators and avoiding the obstructive elements.



(a) The tags placed on 1m x 1m grids (red triangles indicate the positions of locators)



(b) The tags that reach the accuracy below 0.5m

Figure 2-10 Test of system performance (Ham, 2015)

2.5.5 Other Technologies and Application for IPS

Besides to BLE, there are other IPS technologies to track the occupants. For example, optical and thermal cameras are used to capture the images of the monitored objects including occupants; passive infrared (PIR) based motion detectors are used to sense the movement of occupants; carbon dioxide based detection technology detects the concentration of CO_2 to measure occupancy; radio frequency technology such as the GPS, RFID and Device Free Localization (DFL) detects location and activities of occupants; UWB RTLSs use radio signals to detect the movement of occupants (Priyadarshini and Mehra, 2015).

One of the most common indoor positioning applications is retails. Due to the difference in the demand on accuracy, hardware costs, coverage and availability of apps, there is a need to compare and select the technologies for different cases. For example, Camera Analytics has the advantage of up to 100% coverage and no applications are required, but it is more suitable for observation instead of interaction due to its passive technology; VLC (visual light communication) / Li-Fi can reach a high accuracy of four inches; however, the hardware cost is significant and installation of an application is required; Magnetic resonance needs no capital and maintenance costs, but an application is required and the floor plan must be uploaded to the app before the positioning. IndoorAtlas, a provider of magnetic resonance technology, collaborates with Baidu to support its Baidu Maps Location Based Services (LBS). Figure 2-11 shows an example of IndoorAtlas platform, where the blue dot represents the user and the dotted line directs the nearest way to the destination (Statler, 2016).

It is also suggested that deploying the mixture of BLE and any of the above technologies mentioned can provide the best performance of both. Taking the mixture of BLE and Li-Fi for example, the former can trigger the alerts of using the Li-Fi related app and communicate with the control system to save energy by dimming the lighting when the full brightness is not necessary (Statler, 2016).

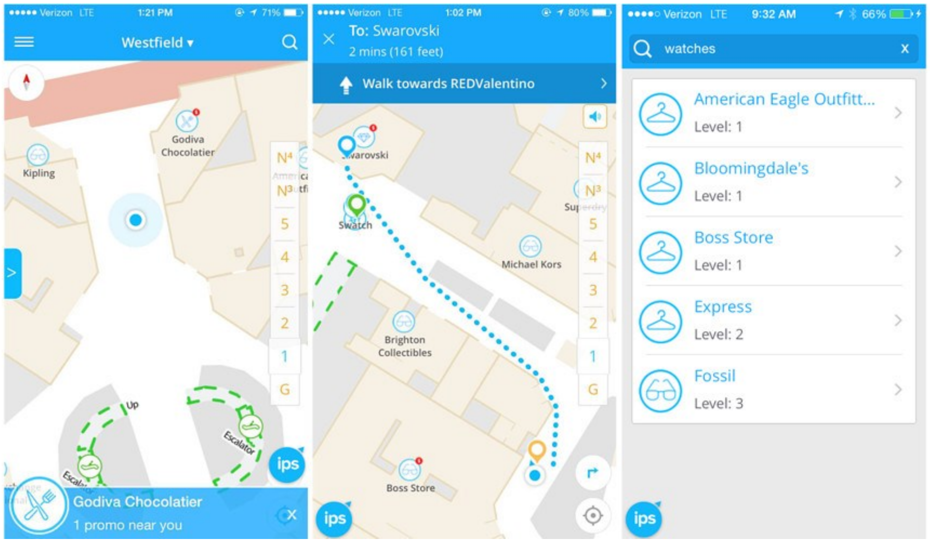


Figure 2-11 IndoorAtlas System (Polleti, 2015)

Regardless of the options and comparisons that help achieve more mature indoor positioning in retails, there is still a fairly challenging problem for this application: if there are apps involved, the consumers have to be interested in the installation and being tracked by the system, which is much more troublesome than simply asking a sales associate (Polleti, 2015).

2.6 Localized Climate Control in Open Spaces

Due to the flexible work hours and large spaces that HVAC systems need to deal with, especially in large offices open spaces, it is more energy-saving to apply localized heating and cooling control to specify the energy needed for occupied and unoccupied areas. Yang & Becerik-Gerber (2014) proposed a room reassignment strategy to arrange the occupants with similar HVAC using schedules in the same mechanical zones. It is concluded that 17% of the energy can be saved, which is a very impressive result. The effectiveness of providing heating/cooling based on a common schedule is proven. However, this strategy may not be applicable in other office buildings because the distribution of occupants is generally based on the nature of their job. Besides, in their research, the preferences of the occupants are not considered.

Lo and Novoselac (2010) developed a localized air flow with occupancy control strategy for cooling and simulated the Computational Fluid Dynamics (CFD) to examine the air quality and to calculate savings in energy consumption. As Figure 2-12 shows, they created an isolated environment in an open office utilizing angled supply jets provided by multiple slot diffusers. The spread of the air movements can be avoided by a central return vent. A two-floor office with one core zone and four perimeter zones on each floor was then modeled in the energy simulation program DOE 2.2. Five cases with different occupancy conditions (occupied or unoccupied) in the ten zones and different temperature set points for cooling (24^{o}C or 29^{o}C) were simulated to quantify the energy savings. It is concluded that 12% of energy can be saved by using the localized airflow control strategy.

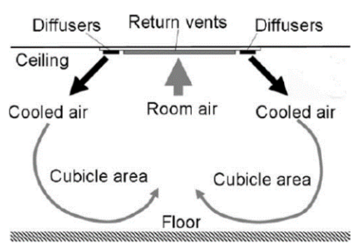


Figure 2-12 Isolated environment utilizing angled supply jets provided by multiple slot diffusers (Lo and Novoselac, 2010)

Gunay et al. (2015) developed an occupancy learning algorithm for terminal heating and cooling units to predict the arrival and departure time of occupants in private offices, leading to 10% to 15% reduction in the annual heating and cooling loads.

Budaiwi and Abdou (2013) proposed several HVAC system operational strategies in Saudi Arabia to reduce the energy consumption in mosques, a unique type of buildings with intermittent occupancy. To save energy consumption, several strategies are proposed. The first strategy is that the HVAC operation precedes occupancy. Secondly, to operate the HVAC system only when the space is occupied, HVAC system is oversized to balance the accumulated thermal load. Thirdly, the conditioned area is divided into zones the according to the schedule and location of occupants (e.g. one zone is occupied on all weekdays and another zone is only occupied on Friday). The simulation results indicate that, as Figure 2-13 shows, 17% and 13% of energy can be saved by the first strategy for un-insulated and insulated mosques respectively; for the second strategy, 36% and 23% of energy can be saved by the second strategy respectively. It is also concluded that savings of 13% and 30% of energy consumption for a mosque with two zones (504 m^2) and another mosque with three zones (1050 m^2) can be achieved, respectively. At the same time, the occupants' thermal comfort is satisfied.

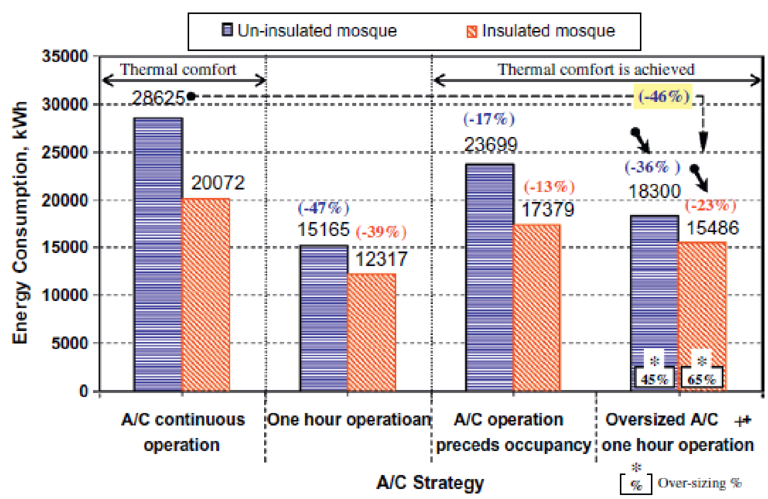


Figure 2-13 Comparison of the energy consumption and thermal comfort before and after using the oversizing and preceding strategy (Budaiwi and Abdou, 2013)

A versatile smartphone application is developed for the employees at the office building called Edge in Amsterdam to dial in their individual climate and lighting preferences for improving the thermal and light comfort (BREEAM, 2015). Packed with 28,000 sensors, The Edge is considered to be the greenest and most intelligent building in the world.

To evaluate the occupancy discomfort level, Salimi, Liu and Hammad (2017) generated an equation as shown in Equation 2-3, where $f_{DCT}(X)$ is the discomfort of temperature level. $DT^{s}_{occ_n,z_H}$ and AT^{s}_{t,z_H} are the desirable temperature for occ_n during season s in zone z_H, and actual temperature of zone z_H during period t in season s, respectively. S stands for season and is used to consider four seasons during a year. Z_H is the number of HVAC systems zones, respectively. T is the total number of time intervals in a day.

$$f_{DCT}(X) = \sum_{s=1}^{S} \sum_{z_H=1}^{Z_H} \sum_{occ_n=1}^{N_{occ}} \frac{\left| DT^{s}_{occ_n,z_H} - \sum_{t=1}^{T} \frac{AT^{s}_{t,z_H}}{T} \right|}{DT^{s}_{occ_n,z_H}} \qquad \textbf{(2-3)}$$

2.7 Building Energy Simulation

In order to design strategies to improve the energy savings and obtain the energy consumption, simulations are usually used because of their ability to (1) vary the factors that are difficult or impossible to control in real environment, (2) calculate the consumption without metering, and (3) save money and time to get the result (Yang and Becerik-Gerber, 2014).

Monfet et al. (2007) modeled Concordia Sciences Building in Montreal, Canada using EnergyPlus and calibrated with the monitored data. Modeling a building using the energy simulation program faces many challenges. They simulated the HVAC system model as two separate entities. After conducting inter-program comparison and calibration, they concluded that the model showed good estimations.

2.7.1 Occupancy Modelling in Building Energy Simulation

Roetzel (2015) discussed the occupancy behavior modelling in building simulation regarding the improvement of the modelling assumptions for cellular offices during the pre-design and sketch design stages where the optimization potential is promising but the input data are limited. Parameters of occupancy schedule pattern, use of office equipment (type of the equipment and intensity of use), natural ventilation (use of operable windows), light control and blind control are explained in terms of the relevance to simulation, architectural design and operational phase and analyzed by comparing an ideal case with a worst case to define the range in the impacts of the parameters, which can be helpful for the architectural decisions in early design stages. As Table 2-2 shows, a numerical example of the comparison is the energy usage of computers, calculated by the energy calculator of EU Energy Star (EU-Energy-Star, 2016) in two occupancy usage patterns, busy office (8h/day) and light office (2h/day).

Table 2-2 Comparison of ideal case scenario and worst case scenario on the energy use of computer (Roetzel, 2015)

Ideal scenario, electricity consumption per year: 21.4 kWh/year		On	Sleep mode	Off mode
Usage pattern	Light office (h)	2	9	13
Equipment	Large notebook 17”–18” (W)	25.5	1.7	0.9
Worst case scenario, electricity consumption per year: 580.3 kWh/year		**On**	**Sleep mode**	**Off mode**
Usage pattern	Busy office (h)	8	2	14
Equipment	Workstation (W)	190	7.4	1.5
	Top 27” LCD (W)	103	1.9	0.6

2.7.2 Building Energy Simulation Programs

Yang and Becerik-Gerber (2014) compared the available energy simulation programs in the market (DOE-2, EnergyPlus, IES-Virtual Environment, ESP-r, and TRNSYS) based on the accuracy and reliability to analyze the effects of occupancy on HVAC energy consumption and response of HVAC system to occupancy-based control strategies (Yang and Becerik-Gerber, 2014). As Figure 2-14 shows, occupancy has an influence on the heat gain (affecting the heat balance and load calculation) and the conditioning requirement (affecting the modeling and simulation of HVAC system) of the buildings. To reach the demands of reducing the energy consumption and at the same time guaranteeing the occupants' comfort and buildings' functionality, the simulation program should couple the occupancy information with the simulation. Based on this, comprehensive comparisons are made of the simulation programs with respect to specialization, heat transfer, load calculation, occupancy-HVAC system connection and the knowledge requirements of the users, etc. they concluded that the qualified programs for the analysis of the occupancy-related effects on the energy consumption are EnergyPlus and IES-<VE>. But due to the complexity of system settings and inaccuracy in modeling the HVAC plants in IES-VE, EnergyPlus, developed by U.S. Department of Energy, is the most suitable among all the reviewed programs. Because of the complexity of writing source code in EnergyPlus, its graphical user interface DesignBuilder makes the simulation more user-friendly and flexible (DesignBuilder, 2015).

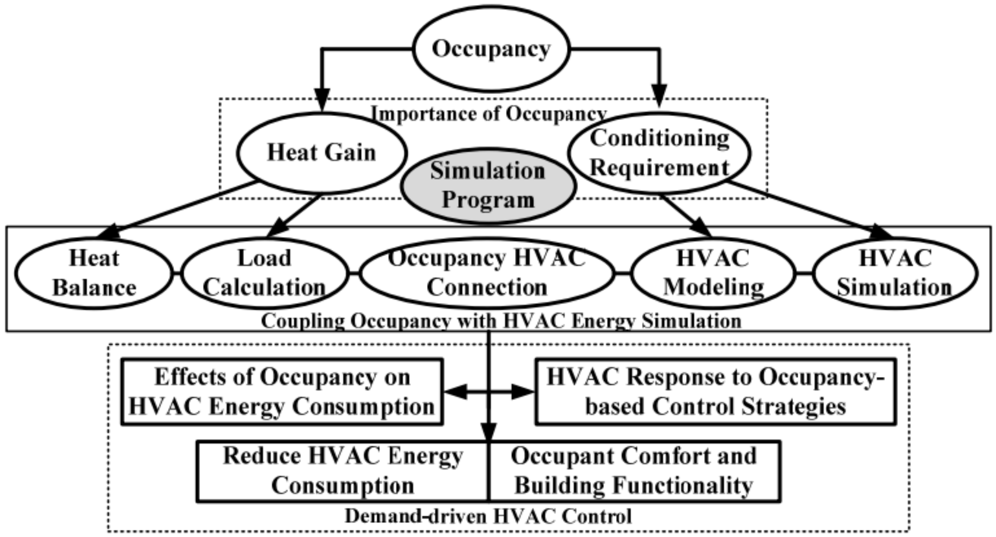


Figure 2-14 Interactions between occupancy and HVAC energy simulation (Yang and Becerik-Gerber, 2014)

2.8 Summary and Conclusions

This chapter reviews the concepts, methods, techniques, algorithms and technologies involved in the current research on occupancy behavior and location sensing.

It is found that occupancy behavior is of great importance for the building energy consumption but the occupancy-related information is often simplified and not emphasized. Most of the research only studied the presence pattern of the occupants in the building. In this research, detailed occupancy profiles including the information of *Who*, *When* and *Where* (*which zone*) in the area of interest will be generated.

To collect the data for the occupancy profile, occupant tracking principles and technologies are also compared and evaluated to select the most suitable system to gain the required occupancy-related information.

Building energy simulation is applied to calculating the energy consumption due to its flexibility in changing the parameters. The energy simulation programs in the market are reviewed and an ideal one is selected for this research.

CHAPTER 3 Proposed Methodology

3.1 Introduction

As explained in Section 2.3 and Section 2.4, building energy performance can be improved significantly by capturing the occupancy behavior and adopting system control strategies accordingly. In this chapter, a local climate control strategy based on the occupants' locations and preferences will be proposed and the steps to investigate the potential energy saving and increase in thermal comfort will be explained.

3.2 Concept of the Method

Figure 3-1shows the overview of the research. First, in open offices with large space shared by multi users, the space is divided into zones according to the number of the HVAC terminal units for the adoption of local climate control. Second, the technologies for the occupancy preference collection, occupancy tracking and building energy simulation are selected. The occupancy tracking technology collects the occupancy information regarding the questions of *Who*, *When*, and *Where,* as explained in Sections 3.3 and 3.4. Then, the output data are processed in two steps: in the first step, the data are visualized and used to generate the occupancy probabilistic profiles for each zone, as explained in Section3.5. In the second step, based on the occupants' preferences and the probabilistic profiles, the occupancy and HVAC operation schedules are created to simulate the energy saving that can be brought by the proposed strategy. The occupants' thermal comfort is also discussed by comparing the discomfort level before and after applying the proposed climate control strategy.

Finally, sensitivity analysis is carried out as described in Section 3.6 to discuss the impact of the factors that tend to affect the performance of the proposed strategy and the HVAC setpoint temperature for occupied and unoccupied conditions.

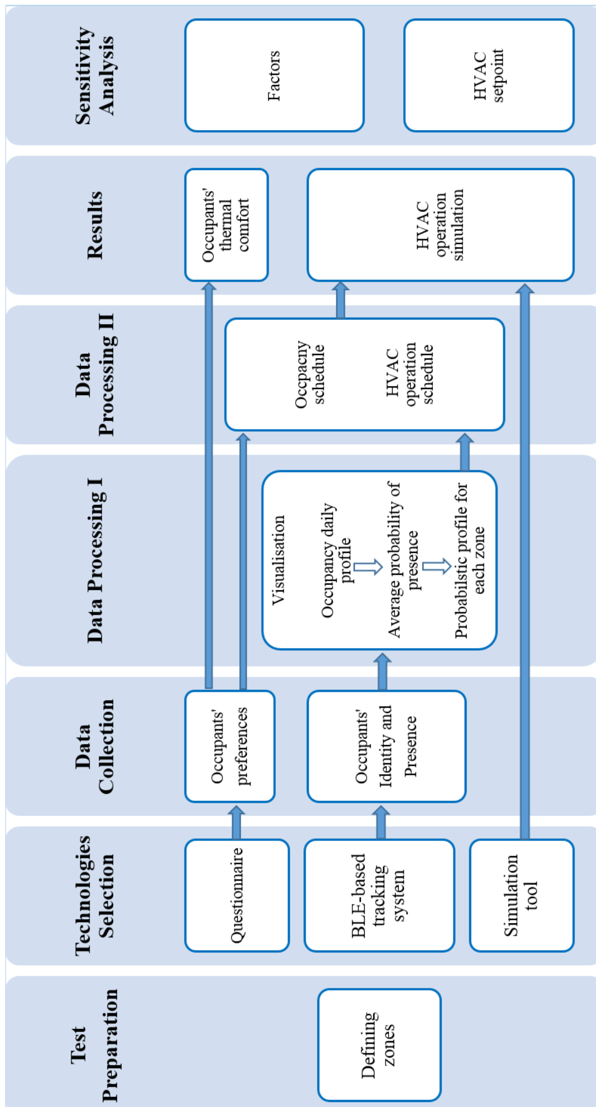


Figure 3-1 Overview of the research

Figure 3-2 shows an example to demonstrate the proposed local control strategy. The figure shows a relatively large open office in a smart building equipped with location sensors (the number of the location sensors depends on the quality of the tracking coverage), and the occupants in the office are wearing tags. The occupancy tracking system captures the identity and location of the occupants at a certain frequency over time. The overall occupancy profiles can be created based on the collected data of the occupants for a specific time period. The probabilistic individual occupancy profiles can be used to identify the specific needs of each occupant and their preferred comfort settings. Assuming that the occupancy pattern is fixed, the resulting profiles can be used for long-term control of light and HVAC settings to avoid the occupants' discomfort and extra energy consumption that may be caused by the delays of system response when depending only on real-time control. These profiles can be also used in the simulation of the energy consumption of the building, which can help forecast long-term energy needs.

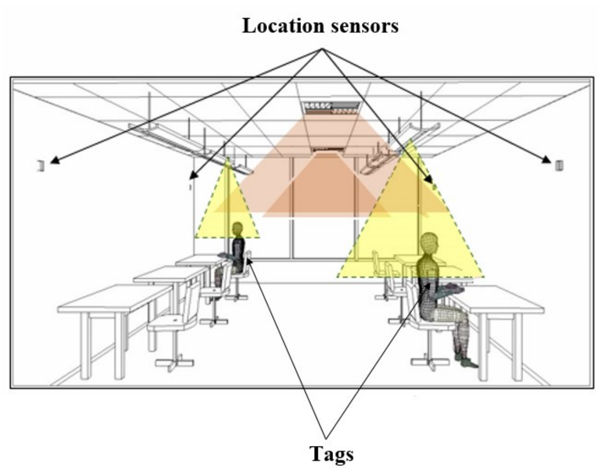
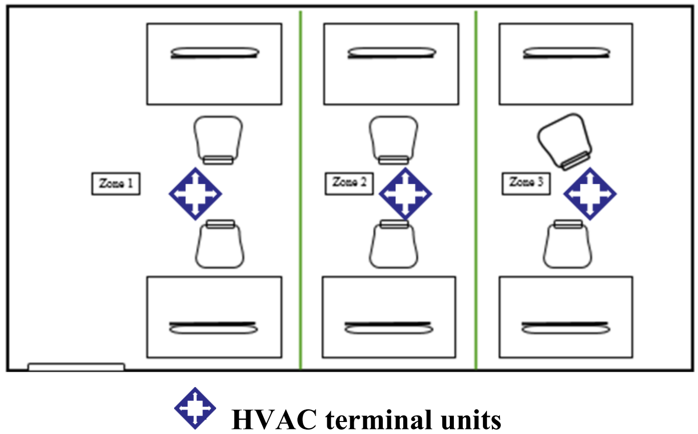


Figure 3-2 Proposed control strategy with occupancy tracking technologies

The area of interest is divided into zones according to the layout of the HVAC system. For example, as Figure 3-3 shows, the office can be divided into three zones according to the number of HVAC terminal units. By capturing the locations of the occupants at the zone level, the HVAC terminal unit in the corresponding zone is activated and adjusted based on the preferences of the occupants in the zone.



HVAC terminal units

Figure 3-3 Dividing the space into zones based on number of HVAC terminal units

The assumptions of the proposed methodology are as follows.

1. The office is an open space with multiple occupants assigned to it.

2. The availability of control is a significant factor. Providing control of the HVAC systems based on individual profiles depends on the availability of individual HVAC terminal units in each zone where the occupants are located. As this condition may not be available in many cases, occupants' profiles should be integrated to match the actual physical layout of the HVAC systems in the specific space based on shared zones.

3. The preferred setpoint temperature of occupants in the same zone are collected and used with the probability of presence to calculate the setpoint temperature applied to the zone to satisfy their comfort to the largest extent.

4. Since the terminal units are sending air flows of different temperatures to the space, the air mixing should be considered. It is assumed that the air mixing of two zones only happens in the boundaries. In the future, the CFD analysis of the proposed local climate control will be conducted and the temperature variations because of air mixing in the space will be investigated.

The flowchart of the proposed method is shown in Figure 3-4. It is assumed that in the area of interest, the total number of the zones is M and the total number of the occupants is N. The number of occupants in Zone z is N_z. The HVAC setpoint temperature of Zone z is defined as T_z. The HVAC setpoint temperature when the zone is unoccupied is set as T_{unocc}. The preferred HVAC setpoint temperature of occupant occ is T_{occ}. The weighted setpoint temperature of the occupants in Zone z is $\overline{T_z}$. There are two loops for zones and occupants respectively. The flowchart goes through Zones 1 to z to check if there is any occupant in each zone. If not, in summer, the HVAC setpoint temperature is set as a relatively higher temperature to avoid unnecessary energy consumption for dealing the thermal loads; if so, occupants 1 to occ are examined to cognize the occupants in the zone, the HVAC system is adjusted to the weighted setpoint temperature based on the present occupants' preferences. The equations to calculate the weighted temperature setpoint will be shown later in Section 3.5.2.

3.3 Occupancy Tracking Technology and Energy Simulation Program Selection

There are various technologies used for indoor positioning. However, to select the suitable technology for a specific case, the requirements for the positioning need to be organized and compared. Based on the parameters that are classified by Wagner and Timmermann (2012), as shown in Figure 2-4, in this research, BLE is selected for tracking the occupants in a relatively large open space and for providing data for the occupancy profile that can be imported to the energy simulation. Bluetooth is a set of wireless technologies for communication between mobile devices in short range. BLE is the enabler of the Internet of Things (Bluetooth, 2015). Compared with classic Bluetooth, BLE is enhanced in the compatibility, protocol stack, link layer state machine, network structure, data packet length, as explained in Appendix A.

Compared with UWB RTLSs and other detection technologies, BLE is less expensive and more practical. Besides, it is much less energy consuming than the classic Bluetooth. The BLE hubs can be any device that implements the BLE standard, such as smart phones. In some cases, the occupants do not have to wear tags as some smart phones can be tracked.

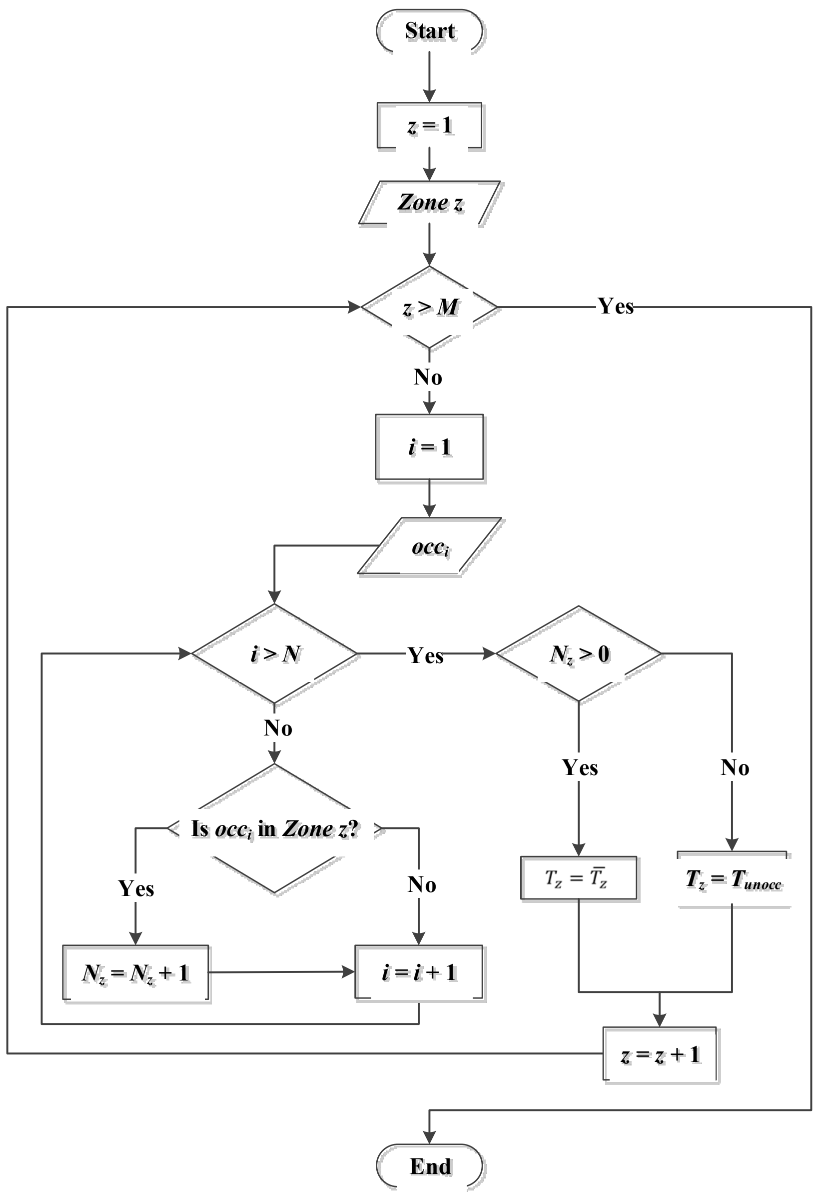


Figure 3-4 Flowchart of the proposed data processing method

Selecting the suitable software for energy simulation is an important decision. Yang and Becerik-Gerber (2014) compared available energy simulation programs in the market based on the accuracy and reliability to react to the effects of occupancy on HVAC energy consumption and response of HVAC system to occupancy-based control strategies. They concluded that the most qualified program is EnergyPlus, developed by U.S. Department of Energy, because of its capabilities for HVAC system simulation. Besides, the graphical interface of EnergyPlus, DesignBuilder, makes the simulation more user-friendly and flexible using the same engine of EnergyPlus (DesignBuilder, 2015). In this paper, DesignBuilder is selected to simulate the proposed HVAC control strategy and to evaluate the energy savings.

3.4 Localizing Technique

An example of the application of BLE is the Quuppa tracking system. The Quuppa tracking system is composed of tags and locators. Tags transmit radio signals, and locators measure the direction of the signal using AoA method. As mentioned in Section 2.5.2, AoA measures the differences in the arrival timings of the signals across different elements of an antenna. If the signal arrives at the same time across all elements, it is perpendicular to the antenna array. As that angle changes, the arrival timing and the phase of the arrival of the signal across the antenna differs. Based on computing that angle, the position of the signal sender can be calculated. As Figure 3-5 shows, the system can determine accurate 2D position using one locator. With two locators, the system is able to obtain accurate 3D position (Quuppa, 2017).

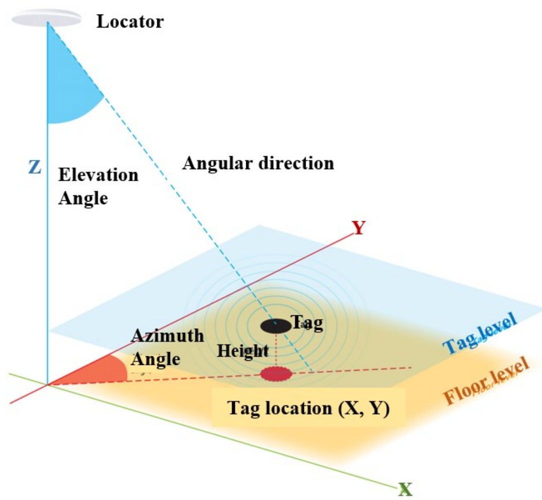


Figure 3-5 Principle of the AOA localizing system (Quuppa, 2017)

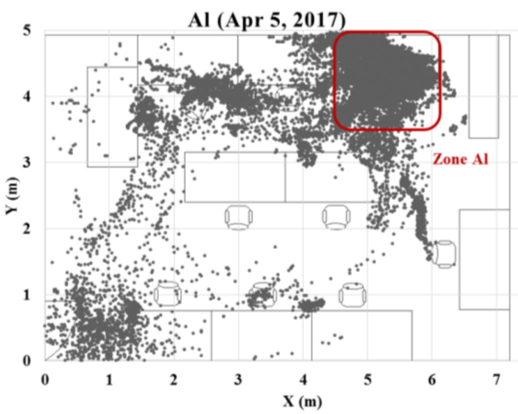
3.5 Data Collection and Processing

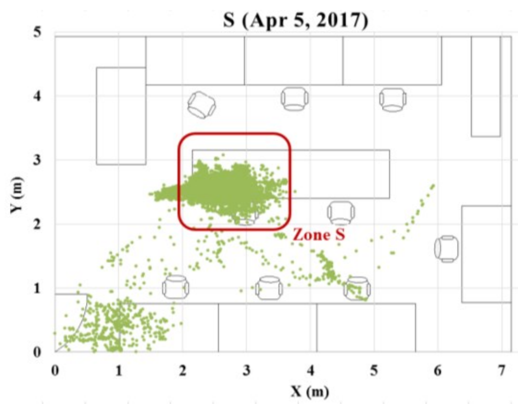
A BLE-based IPS is installed and used to gain the occupancy information regarding the following questions: *Who*, *When*, and *Where*. The preparation process of the setting (planning, hardware setting, locator deployment, tag configuration, validation and monitoring) is explained in detail in Appendix B (Quuppa System Configuration User Manual). The reliability of the tracking system is analyzed when the system is run for testing. The data is visualized by scattered plots and the data replaying application in the tracking system and processed to import as the occupancy profiles to the energy simulation.

3.5.1 Data Visualization

3.5.1.1 Scattered plots

To visualize the distribution of the occupants' positions, the scattered plots are created. For example, occupant Al and occupant S are assigned to Zone Al and Zone S. As Figure 3-6 shows, most of the time, the occupants are in their zone, but they also interact with other occupants or appliances in other zones.





(a) occupant Al **(b) occupant S**

Figure 3-6 Scattered plots showing the movement distribution of the occupants

The scatter plots can only provide the distribution of the occupants' movements, which are related to the *Who* and *Where* questions, but the occupancy schedule cannot be shown.

3.5.1.2 Data replaying

The collected data can be viewed in real-time or replayed using an application in the tracking system. Figure 3-7 is an example of the application interface, which includes the information of all the tags and many functions to view the data. The tags can be chosen individually to replay during the selected time. In addition, the history of the zone in which the tag(s) was present and the percentage of the distribution can be viewed, which will be explained more in Section 4.3.5.1. Compared with the scattered plots, the replaying application can reproduce the occupants' movements associated with time. However, it is not sufficient to merely visualize the data. To further analyze the collected data, occupancy profiles must be created.

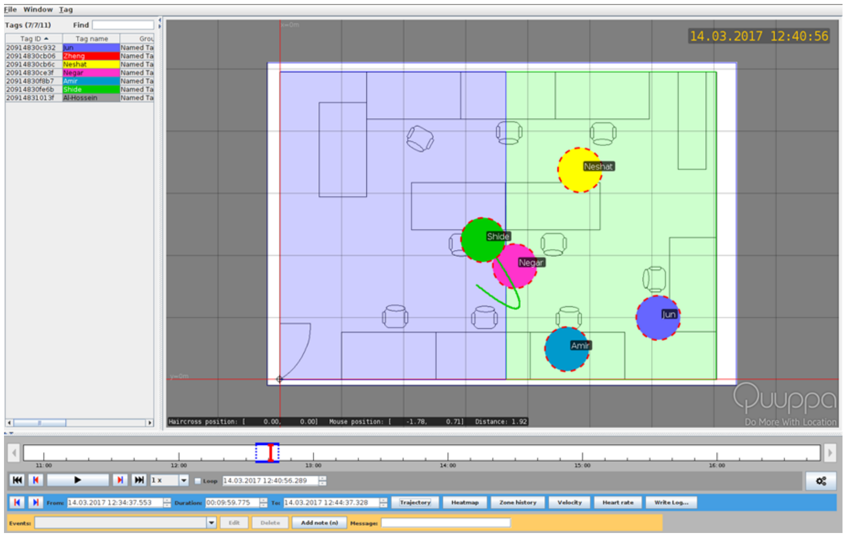


Figure 3-7 Data replaying application in the occupancy tracking system

3.5.2 Occupancy Probabilistic Profile

The probabilistic profile for each occupant shows the probability of the occupant's presence at certain time of the day. This profile can be used for predicting the status of the occupants and adjusting the HVAC system in advance to save energy as well as to satisfy the occupants' thermal comfort.

To obtain the probabilistic profile, a data processing program is developed. In the setting of data logging, the format of the Comma-Separated Value (CSV) file is defined as "Tag name, Date, Time, X, Y, Z coordinates and Zone name". Note the zones shown in Figure 3-5 are the work zones of the occupants. In the simulation, the area of interest is divided into zones based on the number of HVAC terminal units as mentioned in Section 3.2. The logging data is saved as "*.log" and then opened in Microsoft Excel. As shown in the Figure 3-8, to obtain the occupancy profile, the raw data in the defined format is imported to the data processing program, which is composed of two filters: Identification, to divide the data on the occupant-basis, and Time – Location, to acquire the time range per zone per occupant.

After acquiring the occupancy daily profile, the average probability of presence for each occupant is calculated based on the long-term data collection. As sown in Equation 3-1, the presence of occupant *occ* at time interval *t* on day *d* of week *w* is represented by $r_{occ}^{t,d,w}$.

$$r_{occ}^{t,d,w} = 1 \text{ , if occupant } occ \text{ at time interval } t \text{ on day } d \text{ of week } w \text{ is present} \qquad \textbf{(3-1)}$$

$$= 0 \text{ , if he/she is absent}$$

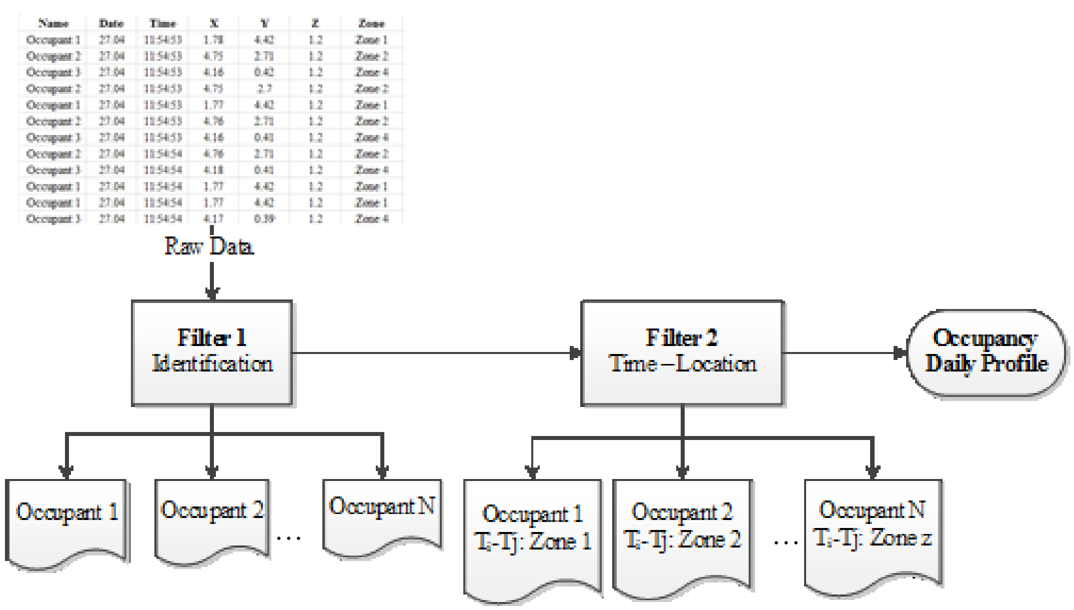


Figure 3-8 Data processing program

The probability of presence $k_{occ}^{t,d}$ for Occupant *occ* at time *t* on day *d* is calculated by averaging the presence of same time and day for all the observed weeks *W*, as shown in Equation 3-2.

$$k_{occ}^{t,d} = \frac{1}{W} \sum_{w=1}^{W} r_{occ}^{t,d,w} \tag{3-2}$$

Then the probabilistic profile for each zone can be computed. As shown in Equation 3-3, for a space divided into *M* zones, the probabilistic profile of all the zones in a week is calculated. For *Zone Z*, there are N_z occupants. The probability of the occupant *occ*'s presence for time interval *t* of day *d* is $k_{occ}^{t,d}$. Therefore, the probabilistic profile for *Z* can be calculated as the average of $k_{occ}^{t,d}$ for all occupants (N_z) in *Z*.

$$P_z^{t,d} = \frac{1}{N_z} \sum_{occ=1}^{N_z} k_{occ}^{t,d} \tag{3-3}$$

Finally, $\overline{T_Z^{t,d}}$, the weighted setpoint temperature of the *Z* at time interval *t* on day *d* is calculated using two methods. The first method is based on the average probability of presence and the setpoint temperature preferences of all the occupants in the zone, as shown in Equation 3-4. T_{occ} represents the preferred setpoint temperature of occupant *occ*. The second method is taking the average value of the setpoint preferences of the occupants that are assigned to the zone, as shown in Equation 3-5. According to the equations, the second method is time-independent, however, the first method adjusts the setpoint based on the availability and the preferences of the occupants at each time interval, which is able to achieve higher level of satisfaction of the occupants' thermal comfort. Therefore, the first method is selected to calculate the weighted setpoint temperature.

$$\overline{T_Z^{t,d}} = \sum_{occ=1}^{N_z} \frac{k_{occ}^{t,d}}{\sum_{occ=1}^{N_z} k_{occ}^{t,d}} \times T_{occ} \tag{3-4}$$

$$\overline{T_Z} = \frac{1}{N_z} \sum_{occ=1}^{N_z} T_{occ} \tag{3-5}$$

It has be mentioned that the first method may involve some problems by giving different weights for the occupants' preferences. For example, an occupant may be sick and needs higher setpoint compared with other occupants. In this case, a higher weight will be given to the occupant. Therefore, to improve the proposed equations, more discussion and adjustment will be done in the future.

3.6 Energy Consumption Simulation

3.6.1 Modeling of the Office Space

The open office with multiple zones is modeled in an energy simulation program. Before applying localized control, the building block model has to be divided into different zones. The general criteria of zoning are: (1) different facade orientation for perimeter zones, because the wind and solar gain changes throughout the day will affect both thermal and daylight control performance; (2) different activity types in different areas, because the change in occupancy and equipment can affect the internal gains; (3) applying bespoke activity data including occupancy schedules, temperature setpoints, etc.; (4) different HVAC system in different parts of the building; and (5) different lighting systems in different parts of the building (DesignBuilder, 2015).

There are two types of partitions, standard and virtual partitions. Standard partitions are used to create enclosed spaces within the block using walls as physical boundaries. Virtual partitions create a new zone without creating a physical boundary. They have no thermal mass and present no barrier to heat and air flow caused by the natural ventilation. (DesignBuilder, 2015). The zones in the open office space are separated by virtual partitions to separate open areas which have different HVAC or lighting systems

To import the probabilistic profile to the energy simulation model, the profile is rewritten in the format that can be read by the energy simulation software, as shown in Table 3-1. The rules of writing the schedules are explained in Section 4.2.3.

Table 3-1 Energy simulation occupancy schedule format

Schedule:Compact, Office_*Zone*$_z$, Fraction, Through: *Day Month*, For: AllDays, Until: t_1, *probability*$_1$, Until: t_2, *probability*$_2$, Until: t_3, *probability*$_3$,

3.6.2 Factors Influencing the Energy Consumption

To examine the effectiveness of the proposed control strategy, three scenarios are generated to quantify the energy saving. Scenario 1 assumes the setpoint of HVAC system is always fixed. Scenario 2 assumes that when there is no occupant in the area, the setpoint of the HVAC system will be adjusted to save energy. When there is any occupancy in the office open space, the setpoint of the HVAC system will be changed to fit the occupants' preferences. Scenario 3 represents the case of localized control. It is assumed that the localized control can be implemented in the large open office with fixed number of users assigned to each zone. The HVAC system can be adjusted according to the occupancy in each zone. By comparing with the baseline (Scenario 1), the energy saving of Scenario 2 and Scenario 3 can be quantified.

Furthermore, to quantify the influence of the combination of several factors on the building energy consumption, as shown in Table 3-2, cases with various values in several factors are conducted in the energy simulation software. The factors are: size of the office, zoning, model complexity (the existence of windows), HVAC operation (fixed setpoint and the availability of local control), occupancy density, assignment of occupancy.

3.6.1 Sensitivity Analysis of the Setpoint Temperature

To quantitatively measure the sensitivity of the energy consumption to the changes in the occupied hours' setpoint and unoccupied hours' setpoint, sensitivity influence coefficients (IC) are introduced (Spitler, Fisher, and Zietlow, 1989). As shown in Equation 3-4, an *IC* indicates the ratio of the percentage change in output to the change in input. OP_{BC} and IP_{BC} stand for base case output and input values. ΔOP and ΔIP stand for the change of values in the output and input. A positive *IC* value means that 1% increase in the input will cause *IC*% increase in the output. On the other hand, a negative *IC* value means that 1% increase in the input will lead to *IC*% decrease in the output. In this case, the input values are the occupied hours' setpoints and unoccupied hours' setpoints, and the output value is the energy consumption of the model.

$$IC = \frac{\Delta OP/OP_{BC}}{\Delta IP/IP_{BC}} \tag{3-6}$$

Table 3-2 Factors involved in the energy consumption

<table>
<tr><th colspan="3">Parameters</th><th>Description</th><th>Expectation</th><th>Cases</th></tr>
<tr><td rowspan="11">Simulation model</td><td colspan="2" rowspan="3">Size</td><td rowspan="3">Size of the office</td><td rowspan="3">Bigger offices can save more energy when the local control is applied. In a literature, it is concluded that savings of 13% and 30% of energy consumption for a mosque with two zones (504 m^2) and another mosque with three zones (1050 m^2) can be achieved, respectively (Budaiwai & Abdou, 2013).</td><td>S_1</td></tr>
<tr><td>S_2</td></tr>
<tr><td>S_3</td></tr>
<tr><td colspan="2" rowspan="2">Zoning</td><td rowspan="2">The criteria of zoning are:
• different facade orientation for perimeter zones
• different activity types in different areas
• applying bespoke activity data
• different lighting systems in different areas</td><td rowspan="2">Applying zoning in the space, the model can save more energy.</td><td>Without zoning</td></tr>
<tr><td>With zoning</td></tr>
<tr><td colspan="2" rowspan="2">Elements</td><td rowspan="2">Mainly refer to windows and office equipment (computers, printers etc.); these elements affect the thermal load for the HVAC system.</td><td rowspan="2">The energy consumption of the model will be more accurate.</td><td>Without windows</td></tr>
<tr><td>With windows</td></tr>
<tr><td rowspan="4">HVAC operation</td><td rowspan="2">Setpoint</td><td rowspan="2">The setpoint is fixed for the HVAC system.</td><td rowspan="2">Setting higher setpoint when the space is not occupied can save energy.</td><td>T_1</td></tr>
<tr><td>T_2</td></tr>
<tr><td rowspan="2">Local control</td><td rowspan="2">The schedule of the setpoint is based on occupant of each zone.</td><td rowspan="2">Operating the HVAC system according to the presence of occupants can save more energy than operating 24/7.</td><td>24/7</td></tr>
<tr><td>When occupied</td></tr>
<tr><td rowspan="4">Occupancy information</td><td colspan="2" rowspan="2">Density</td><td rowspan="2">The density of occupants influences the thermal load for HVAC system.</td><td rowspan="2">Whether denser occupants will increase or decrease the energy consumption depends on their presence patterns and how they are assigned.</td><td>D_1</td></tr>
<tr><td>D_2</td></tr>
<tr><td colspan="2" rowspan="2">Assignment</td><td rowspan="2">• In general, the distribution of the occupants follows the nature of jobs.
• But in some cases, the occupants can be assigned according to the presence patterns or setpoint preferences.</td><td rowspan="2">Reassigning the occupants based on the presence patterns or setpoint preferences can save energy and satisfy the occupants' comfort.</td><td>Random</td></tr>
<tr><td>Schedule-based</td></tr>
</table>

3.7 Summary and Conclusions

In open offices with large space shared by multi users, it is a waste of energy to condition the whole space when it is not 100% occupied. In this chapter, the proposed local climate control strategy based on occupants' locations and preferences is explained. The space is divided into zones based on the number of the HVAC terminal units.

By collecting the occupants' preferences and tracking the occupants' locations at the zone level, the HVAC setpoint temperature of each terminal unit is adjusted based on the calculation involving the preferences of the occupants that are present in the corresponding zone.

The occupancy tracking technology BLE is selected to detect the occupants and to define the zones where each occupant is present due to its high accuracy and saving in power compared with other technologies. The occupants are tracked by wearing tags which the location sensors can communicate with.

By processing the output data of the BLE system, the presence and movement of the occupants are visualized and the profiles of occupants' identity, time, and zone are generated. The probabilistic occupancy profiles can be obtained by long-term tracking and imported as occupancy schedules to the building energy simulation program DesignBuilder. To verify the energy saving brought by the proposed strategy, different scenarios of HVAC operation schedules are created and imported to the selected energy simulation program since it has the flexibility to simulate the adjustment of HVAC setpoint temperature over time of the day at zone level.

Finally, the energy simulation results are compared and analyzed. And the factors affecting the effectiveness of the proposed local climate control strategy are defined. The sensitivity analysis of adjusting the HVAC setpoint temperature is conducted by introducing influence coefficient.

CHAPTER 4 Implementation and Case Studies

4.1 Introduction

In this research, three case studies are designed to investigate the energy saving and the factors affecting the effectiveness of the proposed local climate control strategy based on occupants' locations and preferences. This research runs the simulation for the HVAC system during summer period. Therefore, lighting will be a future work and only cooling is involved for the HVAC system.

The first case study uses the occupancy information regarding the identity, time, and location collected by UWB-RTLSs from a former research and simulates the local climate control based on the occupants' locations to adjust the HVAC setpoint temperature. This case study shows the effectiveness of the proposed local climate control in the conditions that the preferences of the occupants are not accessible. The second case study uses the occupancy tracking technology BLE to collect occupancy information in zone level. The occupants' preferences are acquired as a part of the data collection. Occupancy profiles associated with the preferences are generated for the energy simulation. The applicability of the proposed strategy is discussed and analyzed according to the energy simulation and occupants' thermal comfort. The third case study explores the factors influencing the energy savings of the strategy and conducts sensitivity analysis on the HVAC setpoint temperature.

4.2 Energy Simulation -- Case Study 1

4.2.1 Introduction

A model is created in DesignBuilder, the graphical interface of EnergyPlus. After modeling the building, different schedules are used as input to run the simulation. The schedules of occupancy are firstly imported to the model in DesignBuilder.

To apply the proposed control strategy, a 3D model of an office space is created in DesignBuilder. The model represents an office at Concordia University in Montreal, Canada. The model is shown in Figure 4-1. To define the three scenarios, three HVAC setpoint schedules are generated as input for the model.

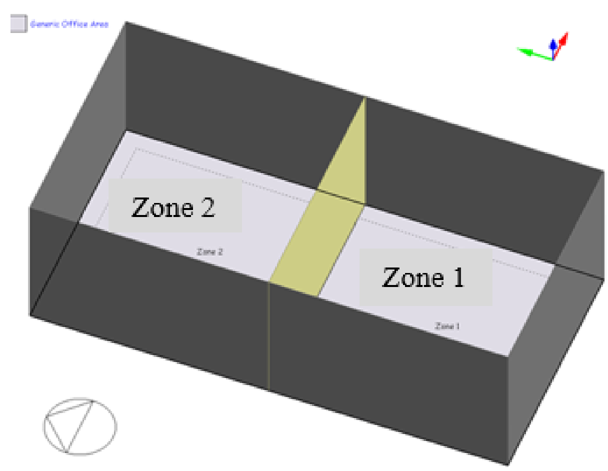


Figure 4-1 DesignBuilder simulation model

4.2.2 Occupancy Schedules

The identity and location of four occupants in the room (M, N, S, L) over one week in June, 2014 are captured by an UWB RTLSs (Masoudifar, 2014). The readings of the tags are updated twice per minute. As Figure 4-2 shows, M and N are under the same terminal unit of HVAC system; therefore, M and N are assigned to Zone 1 of the space. Likewise, S and L are assigned to Zone 2.

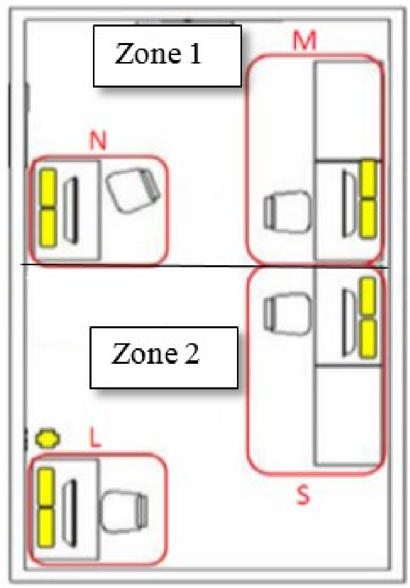


Figure 4-2 Distribution of occupants (Masoudifar, 2014)

As an example of the occupancy data, the percentage of occupancy over time for one week is shown in Figure 4-3. The occupancy schedule is used for the calculation of internal loads for the HVAC system in the three scenarios.

4.2.3 Defining Occupancy and HVAC Operation Schedules

To achieve the proposed control, first, instead of using ideal loads in the modelling by applying the Simple HVAC model in DesignBuilder, it is necessary to apply the Detailed HVAC model made by defining EnergyPlus HVAC systems graphically using components and customizing the setpoints in heating and cooling. There are two types of data in Detailed HVAC model: (1) Simple HVAC data and (2) Detailed HVAC data. In Simple HVAC model and Detailed HVAC/Simple HVAC data, the setpoint can be adjusted in each zone, but the value is constant.

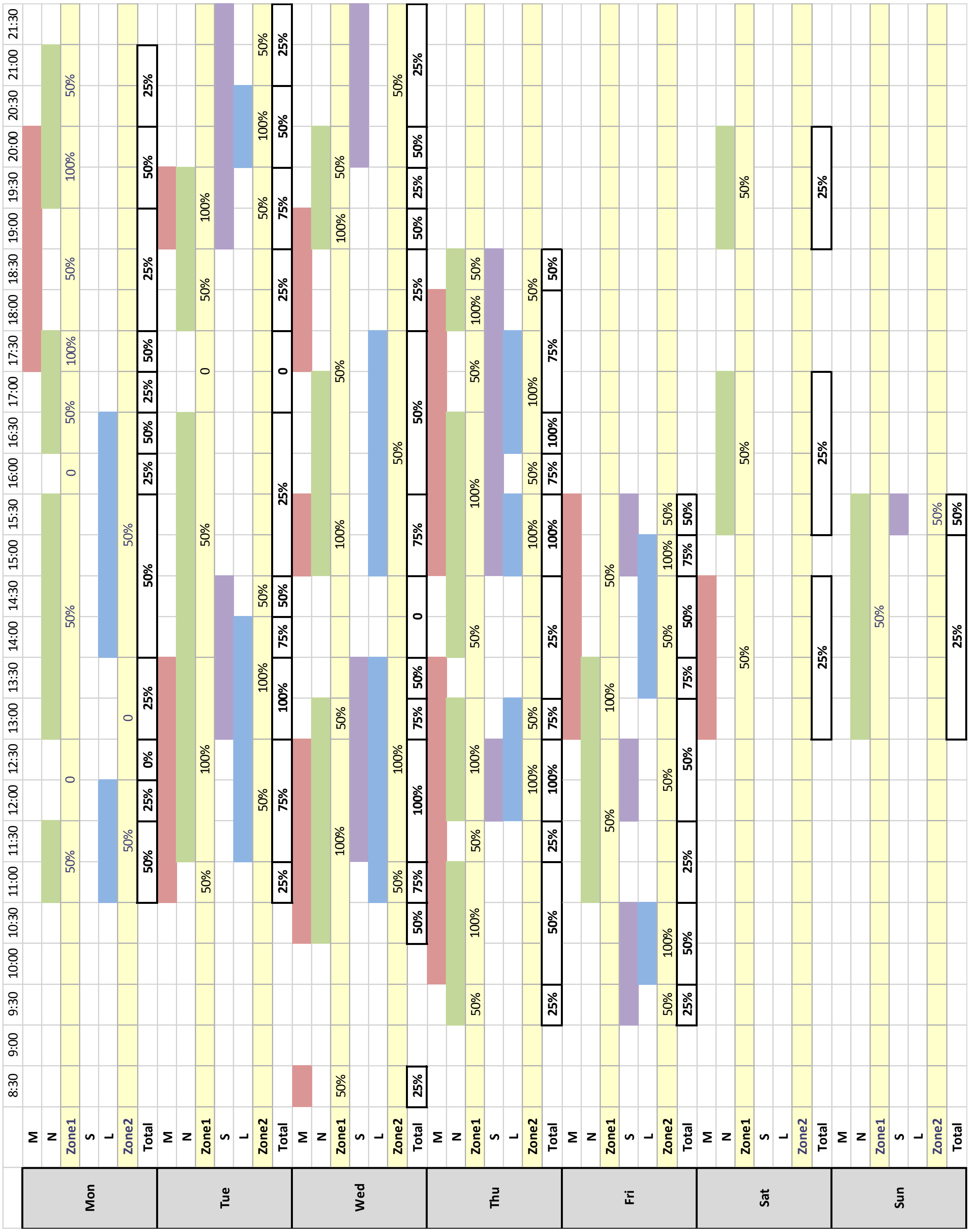


Figure 4-3 Occupants' schedule

In this research, the setpoint should be specified by adding thermostat cooling and heating setpoint schedules according to the occupants' schedules and preferences for the corresponding zones. Therefore, Detailed HVAC model/Detailed HVAC data is selected.

There are two schedule types for the schedule data in DesignBuilder, 7/12 Schedule and Compact Schedule. 7/12 Schedule defines the operation time of seven days of the week and 12 months of the year. However, in this research, a schedule including more detailed information, such as the percentage of the occupants present and the setpoint temperature of the HVAC system, is required.

Therefore, the text-based Compact Schedule, which is more flexible, is chosen to input the schedule. Compact Schedules are defined following a standard format which contains the elements Through (date), For (days), Interpolate (optional), Until (time of day) and Value (percentage of occupancy). The occupancy schedule is described as the time associated with the percentage of the occupants (the occupants present divided by the total number of occupants), and the HVAC operation schedule is described as the time associated with the setpoint of the HVAC system. In the format of compact schedule, the percentage is represented by Fraction and the number is represented by Any Number. Figure 4-4 shows an example of a compact schedule for the occupancy schedule. In the zone called Office_Occ_Z1, on Monday, the time and the percentage of occupants present is listed.

```
Schedule:Compact,
Office_Occ_Z1,
Fraction,
Through: 31 Dec,
For: Monday,
Until: 11:00, 0,
Until: 12:00, 0.5,
Until: 13:00, 0,
Until: 16:00, 0.5,
Until: 16:30, 0,
Until: 17:30, 0.5,
Until: 18:00, 1,
Until: 19:30, 0.5,
Until: 20:30, 1,
Until: 21:30, 0.5,
Until: 24:00, 0,
```

Figure 4-4 Example of a compact occupancy schedule

4.2.4 Defining Cooling Setpoint Temperature Schedules

The HVAC system maintains the indoor temperature to satisfy the occupants' comfort, with a range of from 21°C to 24°C (Murphy and Maldeis, 2009). As shown in Table 4-1, in Scenario 1, the setpoint for cooling is fixed (24°C) on both weekdays and weekends. In Scenario 2, on weekdays, from 8:00 to 18:00, the setpoint is 24°C when there is occupancy in the space and 25°C when it is not occupied; before 8:00 and after 18:00 in the day, the setpoint is 26°C when the space is not occupied and 24°C when there is occupancy. On weekends, the setpoint is 26°C when the space is not occupied and 24°C when there is occupancy in the space. In Scenario 3, on weekdays, when there is no occupancy in the zone, the setpoint is 25°C from 8:00 to 18:00 and 26°C for other periods of the day; when there is occupancy in the zone, the setpoint is adjusted to 24^{0}C. On weekends, for the unoccupied zone, the setpoint is set to 26^{0}C; when the zone is occupied, the setpoint is 24^{0}C.

Table 4-1 HVAC cooling setpoint schedule for three scenarios

<table>
<tr><th colspan="2">State</th><th colspan="3">Not occupied</th><th rowspan="2">Occupied</th></tr>
<tr><th colspan="2">Time</th><th>0:00-8:00</th><th>8:00-18:00</th><th>18:00-24:00</th></tr>
<tr><td rowspan="2">Scenario 1</td><td>Weekdays</td><td colspan="4">24 ^{0}C</td></tr>
<tr><td>Weekends</td><td colspan="4">24 ^{0}C</td></tr>
<tr><td rowspan="2">Scenario 2
(Space-level)</td><td>Weekdays</td><td>26 ^{0}C</td><td>25 ^{0}C</td><td>26 ^{0}C</td><td rowspan="4">24 ^{0}C</td></tr>
<tr><td>Weekends</td><td colspan="3">26 ^{0}C</td></tr>
<tr><td rowspan="2">Scenario 3
(Zone-level)</td><td>Weekdays</td><td>26 ^{0}C</td><td>25 ^{0}C</td><td>26 ^{0}C</td></tr>
<tr><td>Weekends</td><td colspan="3">26^{0}C</td></tr>
</table>

4.2.5 Results and Discussion

After inputting the mentioned occupancy and HVAC operation schedules in the model, the simulation of three scenarios is run for the summer (From 1 July to 30 September). The results are shown in Figure 4-5. By comparing Scenario 1 and Scenario 2, 12% of the energy can be saved at the space level without sacrificing the comfort of occupants. By comparing Scenario 1 and Scenario 3, 13% of the energy can be saved. It can be concluded that the proposed local climate control strategy can reduce the building energy consumption effectively.

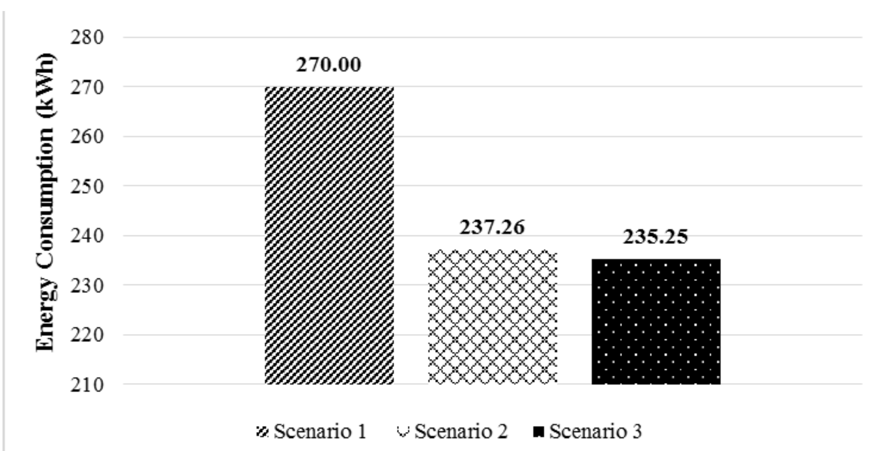


Figure 4-5 Energy consumption of three scenarios

However, it can be noticed that the results show only slight differences between Scenario 2 and Scenario 3. The probable reasons can be:

• The size of the space: It is expected that more significant energy saving can be achieved if the office space is large. As mentioned in Section 2.6 (Budaiwi and Abdou, 2013), with strategies of oversizing the HVAC system and zoning the conditioned area, more energy can be saved in larger spaces.

• The lack of elements in the model: There are no windows in the proposed model, which play an important role in solar gain and energy consumption. Besides, the operation of equipment in the office is not considered, which can affect the heat gain in the space and the consumption of electricity.

• Assignment of occupants: In some office buildings, the distribution of occupants is generally based on the nature of their jobs. However, in some cases, it is possible to obtain more energy savings by the dynamic usage of the space. Reassigning the occupants with similar presence patterns of heating and cooling setpoints to the same office can be one of the solutions to save energy (Yang and Bercerik-Gerber, 2014). In the Edge building in Amsterdam, a strategy called "hot desking" is applied to the office building (BREEAM, 2015). Without assigned seats for the occupants, a specific area in the space can be given precedence for dynamic assignment over others.

• Setpoint: The setpoint can be adjusted within the range of the recommended values in ASHRAE standards. With greater difference in setpoints between the base case (Scenario 1) and other scenarios, the energy consumption difference can be more significant.

• Diversity of occupants' schedules: In Scenario 2, the HVAC cooling schedule is based on the occupancy in the space; but the profiles of the four occupants are of little difference. The similarity of schedules in Scenario 2 and Scenario 3 is a major factor for the similar results.

To explore the factors influencing the effectiveness of the proposed control strategy and quality the influence of these factors, Case Study 3 involves defining the related factors and sensitivity analysis on the setpoint temperature.

4.3 Data collection Using BLE and Energy Simulation– Case study 2

4.3.1 Introduction

To collect the data using BLE technology and involve the occupancy preferences in the simulation, a test of an occupancy tracking system is conducted in a research laboratory Room 9.215 in Concordia University.

The BLE-based tracking system used in this research (i.e. Quuppa) is able to track the latest smartphones and BLE devices with the accuracy of 20-50 cm. The smartphones running BLE 4.1 hardware and Android 5.0 (Lollipop)/API21 or higher can use applications to access the Host Controller Interface (HCI, one of the layers in the BLE architecture) of the BLE chips. As a result, the Quuppa application can transmit the BLE signals that are visible to the Quuppa locators (Grizzly Analytics, 2015).

Based on the measurements made, the size of the room is 5.0 m×7.0 m×3 m. Figure 4-6 shows a picture of the room. There are six graduate students assigned to the room whose names are marked in the figure. The layout of the room with the setup of the tracking system is shown in Figure 4-7.

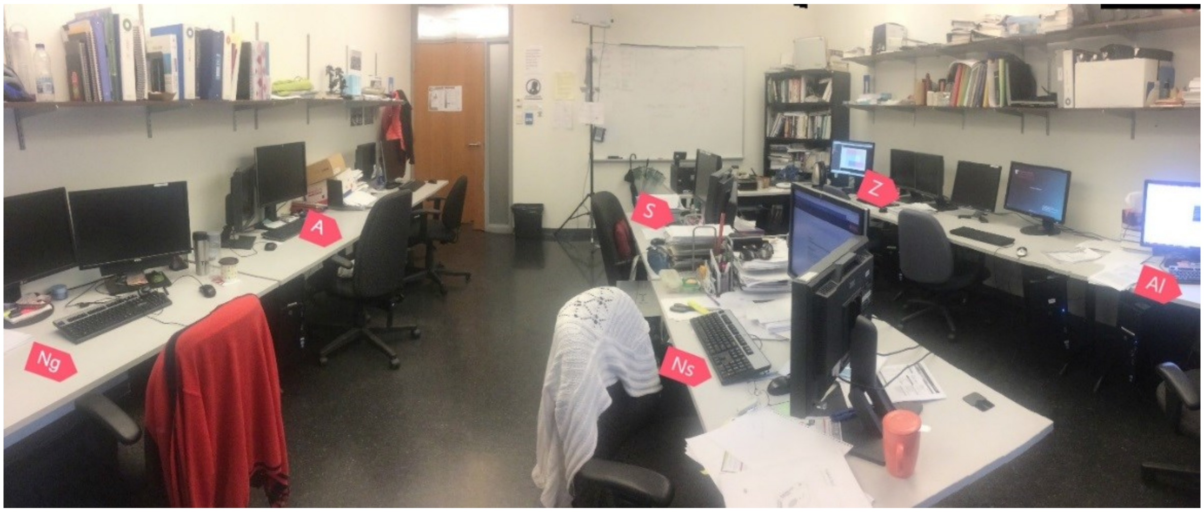


Figure 4-6 Picture of the laboratory

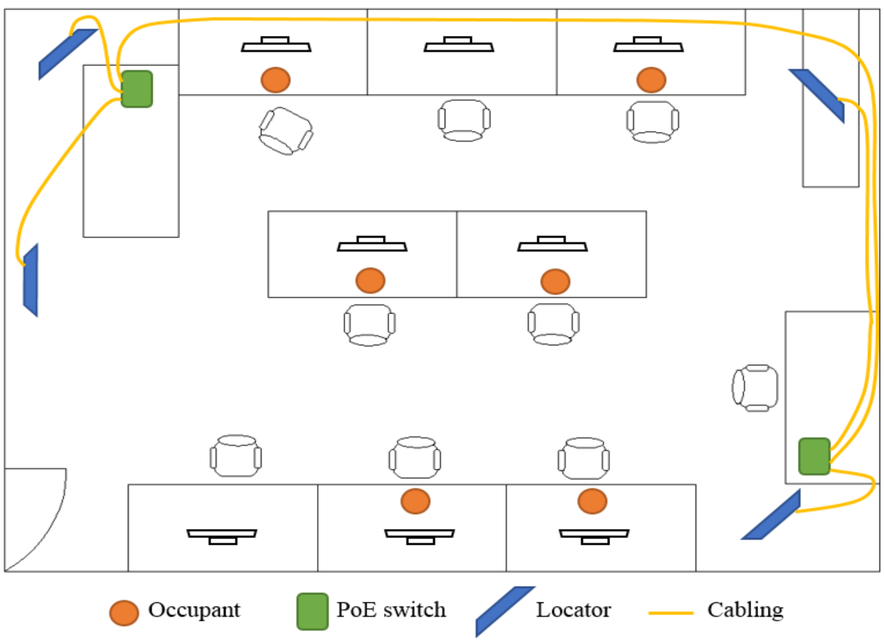


Figure 4-7 System layout

4.3.2 Experiment Setup

4.3.2.1 Planning

In addition to the Quuppa Demo Kit (Quuppa, 2017), other devices and equipment that are employed in the experiment are shown in Table 4-2.

Table 4-2 Contents of the experiment

Quantity	Description	
1	LD-6L Focusing Locator	Quuppa Demo Kit
1	Mounting bracket (holding LD-6L Focusing Locator)	
4	LD-7L Locators (IDs are seen in Appendix B)	
7	LD-6T Tags	
1	Controller Server PC (Apple Mac mini)	
1	Type C power cord for Apple Mac mini	
1	USB-to-Ethernet Adapter	
1	Display with HDMI connection	
1	USB keyboard	
1	USB mouse	
2	PoE (Power-over-Ethernet) Switch	
7	Cables	
4	Wood panels	
2	Mounting stands (holding LD-7L Locators)	

The system is physically set up according to the Quuppa Tracking System User Manual, as shown in Appendix B. Laser measurements are used to obtain the size of the room. Then, a plan of the room is created in AutoCAD and imported to the Quuppa Site Planner & Deployer application as a background image as shown in Figure 4-8. For the data collection, according to the distribution of seats, each occupant (A, Ng, Ns, S, Al, and Z) is assigned to a zone of $1.40 \times 1.53\ m^2$; the zones that will be occupied in the future are named *Vacant 1* and *Vacant 2*; the zone ($1\times1\ m^2$) near the door of the room is named *Door*; the other spaces are named *Public 1* and *Public 2*. In *Public 1*, occupants use the printer and the kettle. In *Public 2*, the occupants use the lockers. Note that *Public 2* is close to the window. The different colors in the space show the zoning.

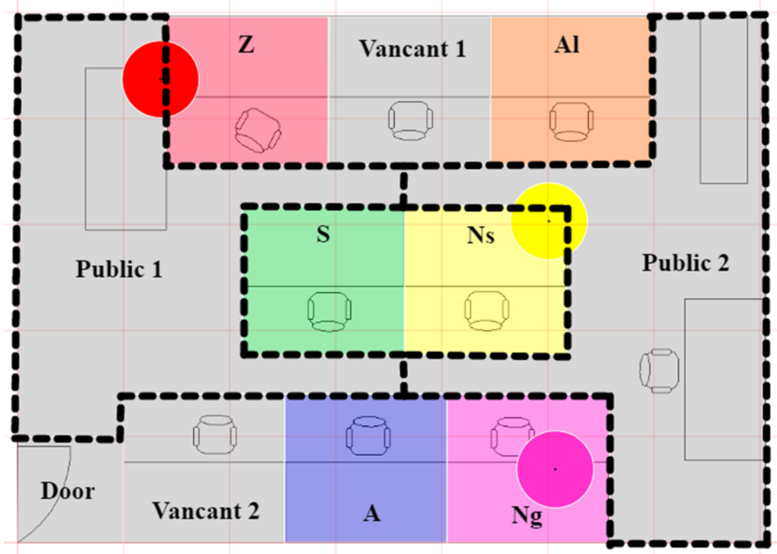


Figure 4-8 Zoning of the space shown in the software

4.3.2.2 Locator deployment

According to the installation mannual, the locators should face down to the area of interest, which makes the ceiling the best surface to install them. However, due to safety concerns, the locators are placed on the mounting stands or on spots with tilt angles to face down and obtain a relatively good coverage. The coverage quality estimate can be checked in the Quuppa Site Planner. As shown in Figure 4-9, red color represents bad quality and green color represents good quality. The coverage quality of four locators in the room (the red lines are x axis and y axis) is good for tracking. To make the locators stable and out of the occupants' reach, two locators are placed on the top of two bookshelves and the other two are installed on mounting stands, as shown in Appendix B.

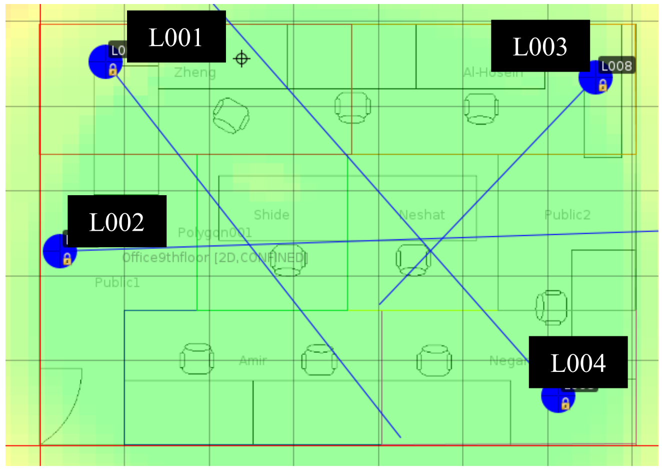


Figure 4-9 Coverage quality estimate of the locators

The locator kits are placed in the premises according to the plan and connected to the PoE switch. Laser measurements are used to get the accurate locations and heights of the locators. The coordinates are used to define the positions in the QSP and locators' IDs and orientation are configured. Table 4-3 shows the coordinates of the four locators, indicating the positions in the room where (0, 0, 0) is the lower left corner in Figure 4-8. In addition, all of the locators are attached to wood panels using standard ties and steel wires to make it easier to adjust the tilt angle.

Table 4-3 Coordinates of the locators

Locator	X coordinate (m)	Y coordinate (m)	Z coordinate (m)
L001	0.79	4.56	1.83
L002	0.25	2.19	2.22
L003	6.41	4.28	2.03
L004	6.13	0.48	1.83

4.3.2.3 Tag configuration

The tags are configured to be in three states based on different movements of the occupants: (1) *Triggered state* (when a motion is detected and the transmit rate is very high), (2) *Default* *state* (when there is no motion but the tag still sends signal in a lower rate), and (3) *Storage state* (when the tags fall asleep). The transmit rate, transmit power and state timeout of the states are customized in the application. To gather enough data and save the battery of the tags at the same time, as Figure 4-10 shows, the transmit rates of *Triggered* and *Default* states are defined as 3 Hz and 0.10 Hz, respectively. To save the battery of the tags, the timeouts of *Triggered* and *Default* states are set as five minutes and one hour, respectively, which means after the tag is triggered, if there is no motion detected in five minutes, the tag will go to *Default state* and if there is no motion detected in one hour, the tag will fall asleep (*Storage state*). After activating the tags, the tag configuration and tag names are defined in QSP. The tags are named after the occupants to whom they are assigned.

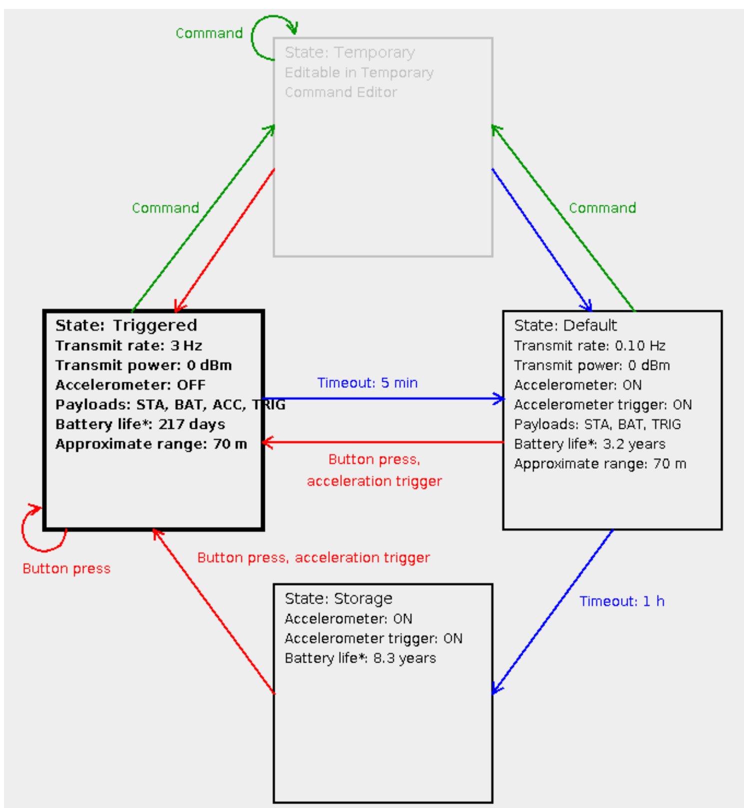


Figure 4-10 Setting of the tag configuration

4.3.2.4 Logging format

In order to better analyze the collected data, the CSV (comma-separated value) format is defined as the output data format. Following the given pattern of command, the output format is customized as “Tag ID, Date, Time, X, Y, Z coordinates” in the UDP/logging/API Editor. Also, the Quuppa Data Player and Live View are configured to start automatically when the system starts.

4.3.3 Data Collection

The tags are attached to the occupants using lanyards. Each occupant is assigned with a tag marked with his/her name. The tags are activated when sensing movement. After starting the server and opening the Positioning Web Console, the information tables of tags and locators are available on the web console to check the conditions, and the tags are shown on the 2D and 3D Map Views. Therefore, the following tracking conditions can be checked all the time.

- Whether the tag is shown when the occupant is present;
- Whether the tag is moving according to the occupant’s movement;
- Whether the tag is not shown or out of the area of interest when the occupant is absent.

When the occupants leave the tracking area at the end of the day, they left their tags on the tables and the update rates gradually drop down until the tags fall asleep based on the tag configuration.

4.3.3.1 Collection of the ground truth and occupants’ preferences

To validate the data processing program in the next step, a check table is created to collect the ground truth of the occupants’ arrival, lunch break and departure time. Figure 4-11 shows an example of the check table on Monday, May 15, 2017, for the occupants’ first arrival and last departure. Note that if the occupants arrive or leave at a time that is not shown on the chart, they can write down the specific time.

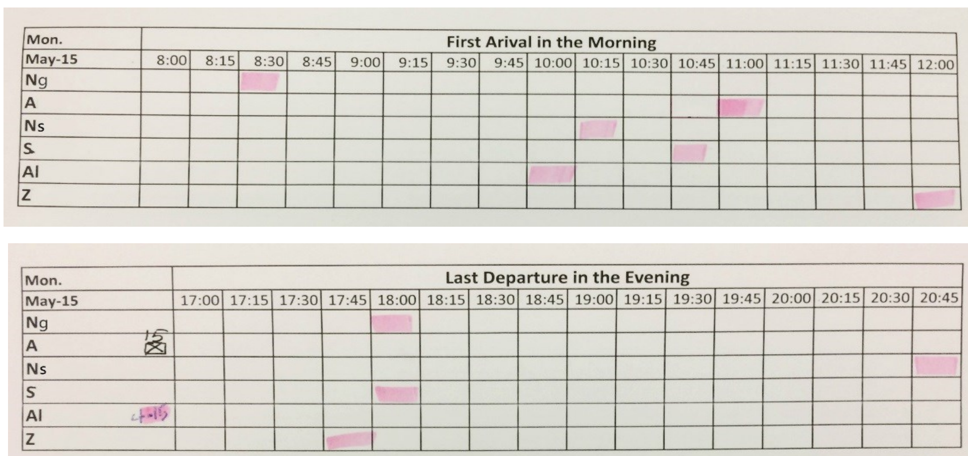


Figure 4-11 Check tables recording the ground truth

As mentioned in Figure 3-3, the HVAC and lighting systems should be adjusted according to the probabilistic profiles and preferences of the occupants. Therefore, the occupants’ preferred setpoint temperature should be known. The cooling setpoint temperature preferences are collected and listed in Table 4-4.

Table 4-4 Occupants' preferred cooling setpoint temperature

Zone	Occupant	Preferred setpoint (^{0}C)
Zone1	Z	25
	S	22
	A	24
Zone2	Al	22
	Ns	24
	Ng	22

4.3.4 System Verification

4.3.4.1 Tracking accuracy verification

A short-term test is run to assure the reliability of the data collected by the tracking system. The collected data and the actual paths the occupants move (ground truth) are compared. The file created by the UDP/logging/API Editor of the tracking system is opened and processed in Microsoft EXCEL. The data is sorted by tag ID and a graph is created to show the x and y coordinates of different tags. In the test, occupant 1 wears Tag 1 and stays still in the room; occupant 2 wears Tag 2 and walks following straight lines marked on the floor. As Figure 4-12 shows, the scattered plot represents the changes in the position of different tags, and the actual paths are marked using black lines.

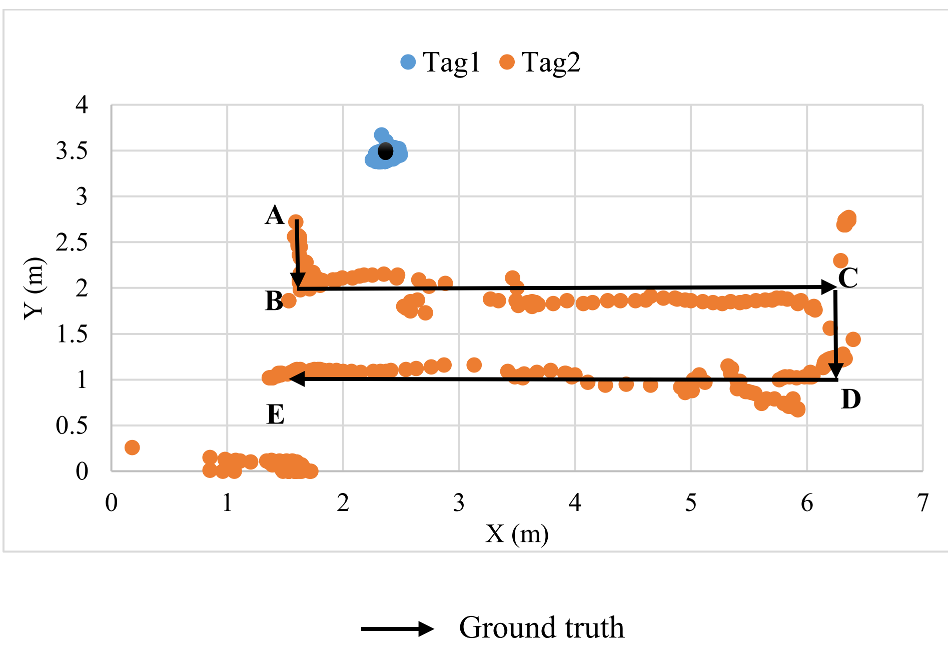


Figure 4-12 Occupants' paths shown in Excel

The difference of the collected tag locations and the actual paths is calculated using Equation 4-1. For example, from point A to B, x_{occ}, the x coordinate of the occupant remains to be 1.6

m, therefore, the absolute value of the difference between the x coordinate of collected data and 1.6 is summed up and divided by the number of the readings in the data collected. The result shows that the average difference is 0.06 m. It can be concluded that the data collected by the tracking system is reflecting the actual movement.

$$\frac{\sum_{occ=1}^{N_Z}|x - x_{occ}| + \sum_{occ=1}^{N_Z}|y - y_{occ}|}{n} \qquad \textbf{(4-1)}$$

It is noticed that in the Tag configuration, the transmit rates of *Triggered state* and *Default state* are set to 3 Hz and 0.1 Hz, respectively. The actual transmit rates for the two states shown in the test result are 4.52 Hz and 0.15 Hz, respectively.

4.3.4.2 Extending the boundary of the tracking area

To investigate the possible problems concerning the space layout, project design, occupancy behavior and other exterior factors to the tracking system itself, another one-day test is run on from 11:00 to 17:30 on March 29, 2017. A problem is noticed that when the occupants are absent, there are still data collected by the system indicating they are inside the room.

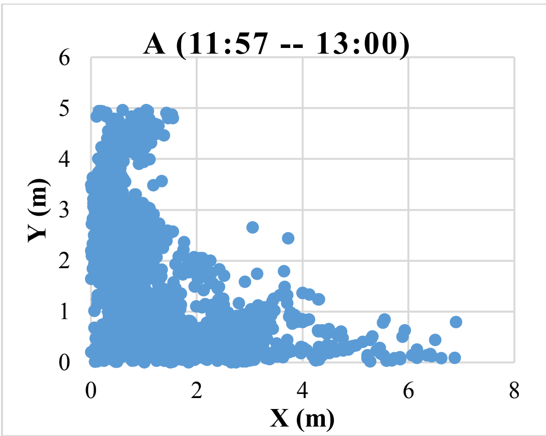
During the test, the ground truth is collected by taking notes of the occupants' activities within the day. As shown in Table 4-5, the ranges of time that the occupants are absent from the room are listed and compared with the amount of data collected during the corresponding time. The cases that there are data obtained when the occupants are absent are given numbers 1 to 9.

According to the comparison, in cases 4, 5, 6, 7 and 8, the amount of data is much less than cases 1, 2, 3 and 9 since the occupants are leaving or entering the room and they do not stay in the corridor for long. Based on the ground truth, in cases 1, the occupant made phone calls in the corridor right beside the room and left the lab; in cases 2 and 9, the occupants made phone calls in the corridor and entered the room; in case 3, the occupant stayed in the corridor for a while (2 minutes).

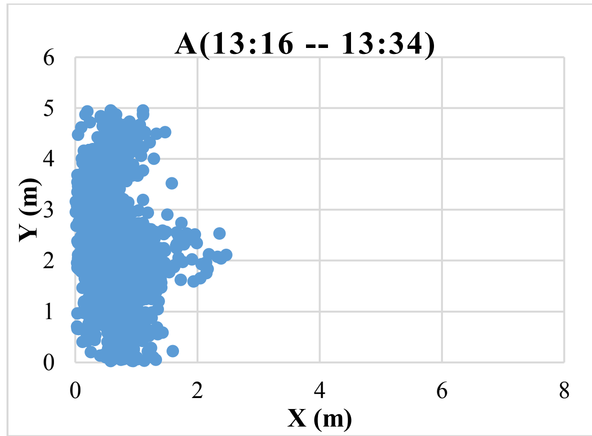
Table 4-5 Occupants' absence schedule and collected readings in the corresponding period

Occupant	Ground truth (Absence schedule)	Number of readings	Location	Case
A	11:57 – 13:00	2155	corridor	1
	13:16 – 13:34	2582	corridor	2
	13:50 – 15:21	0		
	15:25 – 17:30	346	corridor	3
Ng	12:49 – 12:58	170	corridor	4
	13:18 – 13:44	0		
	13:51 – 15:21	0		
	16:00 – 16:10	61	corridor	5
Ns	12:01 –14:49	0		
	15:13 –15:15	161	corridor	6
	15:16 – 17:13	83	corridor	7
Z	11:15 – 11:17	0		
	11:44 – 11:46	132	corridor	8
	13:35 –14:01	0		
	14:13 –14:20	951	corridor	9
	16:13 –16:33	0		
	17:27 –17:30	0		
S	13:18 – 13:44	0		
	13:49 – 15:21	0		
	15:25 –15:28	0		
	15:47—17:09	0		
	17:13 – 17:30	0		

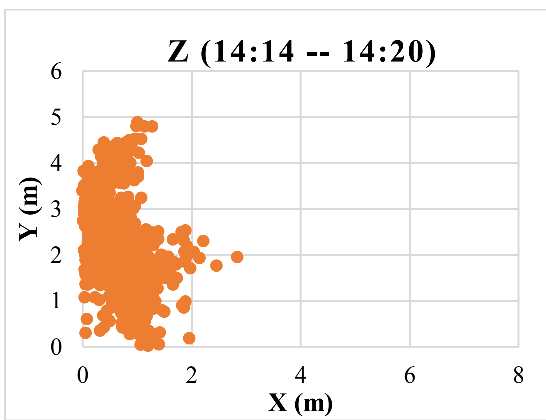
The collected data of cases 1, 2, and 9 are plotted as scatter diagrams in Figure 4-13. The figures show that the locators detect the signals of the tags through the wall and because there is no extra space in the background image in the created project, the data shows that the tags are distributed near the wall, from (0, 0) to (0, 6). Therefore, the problem can be solved by expanding the background image so that the tags can be shown outside of the room when the occupants are in the corridor.



(a) Case 1



(b) Case 2



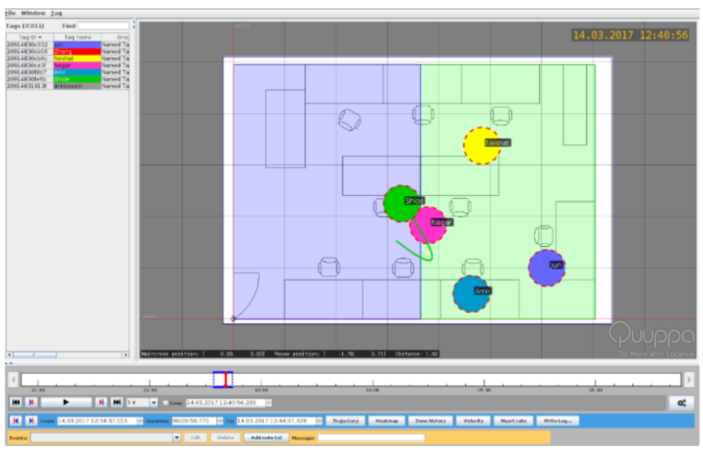
(c) Case 9

Figure 4-13 Tags detected when the occupant is in the corridor

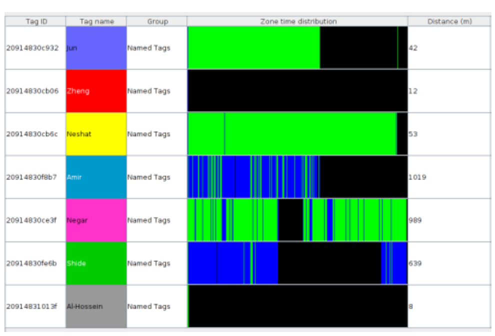
4.3.5 Data Processing

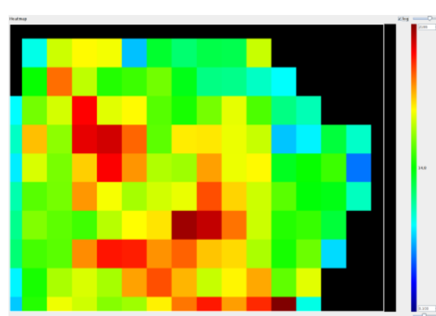
4.3.5.1 Visualization of recorded data in Quuppa

After collecting the data, the QDP (Quuppa Data Player) allows to review of the recorded data with respects of the paths occupants followed, the percentage of the time that each occupant spends in each zone, and the heat map during the recorded time. The occupants' paths in Figure 4-14 (a) show all the movements of the occupants, which is the replay of the passed tracking time. As can be seen in Figure 4-14 (b), the occupancy-time chart indicates the length of the time that the occupants spend in each zone. The heat map in Figure 4-14 (c) can be used to define the most occupied area of the space.



(a) Occupants' paths





(b) Occupancy-Time proportion for each zone **(c) Heat map**

Figure 4-14 Data visualization enabled by the Quuppa system

4.3.5.2 Occupancy daily profile

After running the occupancy tracking system for four weeks, as mentioned in Figure 3-8 of Section 3.7.2, the raw data is processed by the data processing program in MatLab, as shown in Appendix C, to obtain the occupancy daily profile. Figure 4-15 shows an example of the daily profile for the six occupants on one day. As can be seen in the profile, there are the start and end times of staying in a zone for each occupant. It is assumed that if the occupant stays in a zone for less than five minutes, the data during the stay is eliminated since the according frequent adjustments of the HVAC system can result in more energy consumption and discomfort of occupants. The daily profiles are used to create the weekly occupancy probability of presence.

	Name	Start	End	Zone
5/15	Z	12:12	12:37	1
		12:56	16:20	1
		16:33	17:36	1
	Al	10:47	12:14	2
		12:15	12:36	8
		12:36	13:18	2
		15:49	16:15	2
	A	10:43	11:34	3
		11:42	12:44	3
	Ng	9:46	10:08	4
		11:25	12:48	4
		13:14	13:32	4
		14:30	16:56	4
		17:04	17:57	4
	Ns	14:34	15:33	5
		16:14	16:24	5
		16:33	20:48	5
	S	10:44	10:58	6
		11:04	13:31	6
		14:23	14:39	6
		14:48	15:19	6
		17:49	18:02	6

Figure 4-15 Occupancy daily profile

4.3.5.3 Validation of the data processing program

To validate the data processing program, a comparison is made between the ground truth recorded by the check table, and the output of the program. The comparison is displayed in

Appendix D. There are some cases that some differences between the arrival time and the start of the profile is assignable. The review of the raw data in these cases show that the occupants arrive and leave the room after a short stay (less than five minutes). Hence, it can be concluded that the daily profiles are in accordance with the ground truth.

4.3.5.4 Occupancy probabilistic profiles

As mentioned in Equation 3-1, the weekly occupancy probability of presence is for occupant *occ* at time *t* on day *d* calculated by averaging the presence condition for time *t* on day *d* for all the four weeks. The time step is set to 30 minutes. Table 4-6 shows an example of the obtained weekly probability of presence for occupant Ng on Thursday.

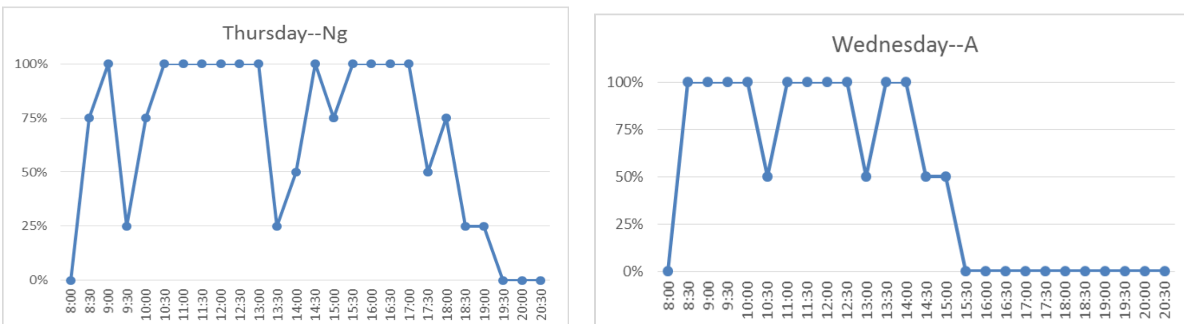
Table 4-6 Example of the weekly occupancy probability of presence (Ng, Thursday)

8:00	**8:30**	**9:00**	**9:30**	**10:00**	**10:30**	**11:00**	**11:30**	**12:00**	**12:30**	**13:00**	**13:30**	**14:00**
0%	75%	100%	25%	75%	100%	100%	100%	100%	100%	100%	25%	50%

14:30	**15:00**	**15:30**	**16:00**	**16:30**	**17:00**	**17:30**	**18:00**	**18:30**	**19:00**	**19:30**	**20:00**	**20:30**
100%	75%	100%	100%	100%	100%	50%	75%	25%	25%	0%	0%	0%

After calculating the weekly probability of presence for all the occupants for the whole week, line charts are used to demonstrate the trends of the probability. It can be noticed that the occupants have two types of schedule patterns: flexible and consistent.

Some occupants have flexible schedule, such as the probabilistic profile for occupant Ng on Thursday shown in Figure 4-16 (a). The occupant arrives between 8:30 to 9:00 in the morning and is very likely to leave the zone after a short stay to get prepared for the day. From 10:30 to 13:00, the occupant stays in her zone until the lunch break between 13:30 to 14:30. In the afternoon, the occupant works until around 18:00 and sometimes 19:00. There is also another type of presence pattern, which is very consistent. As shown in Figure 4-16 (b), occupant A arrives on Wednesday at 8:30 and stays until 15:30, with regular short breaks during work. By comparing these two types of schedule, it can be concluded that the flexible type calls for a long-term data collection to assure the reliability of the data. However, for the occupants with the consistent schedule, it is easier to capture and predict the pattern of their presence.



(a) Flexible pattern **(b) Consistent pattern**

Figure 4-16 Examples of weekly probability of presence

Also, the average hourly occupied time distribution can be analyzed in the High-Low-Close chart, as shown in Figure 4-17. The highest point show the longest presence time in the zone during the hour on the day among the four weeks; the lowest show the shortest presence time and the green dot show the average presence time.

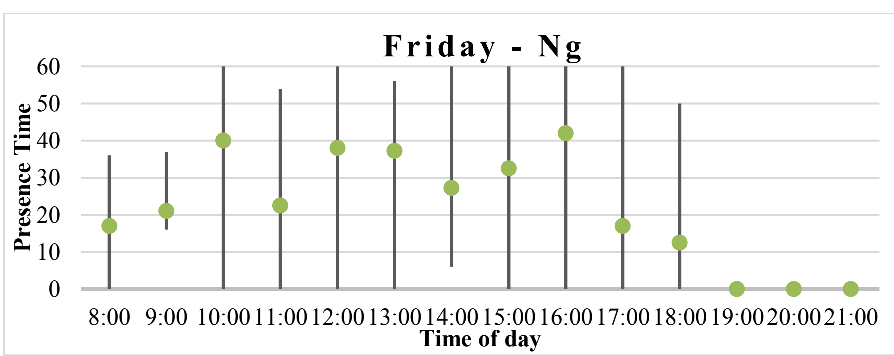


Figure 4-17 Average hourly occupied time distribution

The probabilistic profile for each zone is calculated using Equation 3-2. As explained in Section 4.3.2.1, the space is divided into eleven zones based on the distribution of seats of the occupants. However, for the energy simulation, the whole space is divided into two zones according to the number of HVAC terminal units according to the proposed local climate control strategy. Therefore, occupants Z, S, and A are assigned to Zone 1 and Al, Ns, and Ng are assigned to Zone 2. Since there are three occupants in each zone, n_1 and n_2 in Equation 3-2 are both equal to three. An example of Zone 2 on Thursday is shown in the Table 4-7.

Table 4-7 Example of the probabilistic profile (Zone 2, Thursday)

Thu	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00
Al	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ns	0%	0%	0%	50%	50%	50%	100%	100%	100%	0%	100%	50%	50%
Ng	0%	75%	100%	25%	75%	100%	100%	100%	100%	100%	100%	25%	50%
Total	0%	25%	33%	25%	42%	50%	67%	67%	67%	33%	67%	25%	33%

Thu	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30
Al	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ns	100%	100%	50%	50%	50%	50%	50%	50%	50%	0%	0%	0%	0%
Ng	100%	75%	100%	100%	100%	100%	50%	75%	25%	25%	0%	0%	0%
Total	67%	58%	50%	50%	50%	50%	33%	42%	25%	8%	0%	0%	0%

The probabilistic profiles for Zone 1 and Zone 2 for a week are plotted in line charts and shown in Figure 4-18 and Figure 4-19, respectively. Comparing the weekdays and weekends for both zones, it can be concluded that the room is much less occupied during the weekends, especially in Zone 1. Also, the lunch break of Monday to Thursday can be seen where there is a dramatic drop in the probability of presence. As for Friday, each occupant has a different schedule for lunch because of the weekly meeting with their supervisor. Besides, there is a trend that the zones are slightly less occupied on Monday compared with other weekdays, and the occupants tend to leave early on Friday.

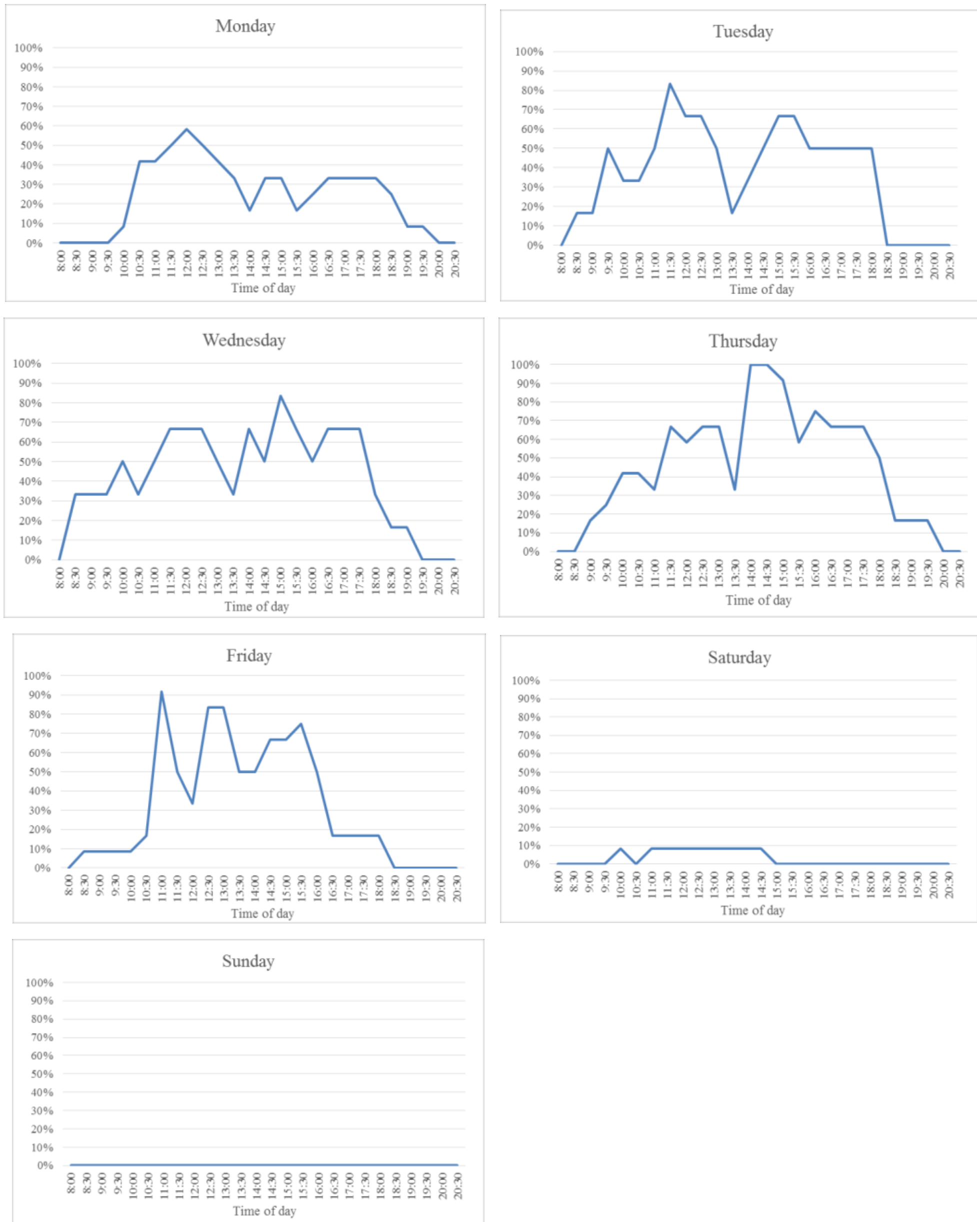


Figure 4-18 Probabilistic profile of Zone 1

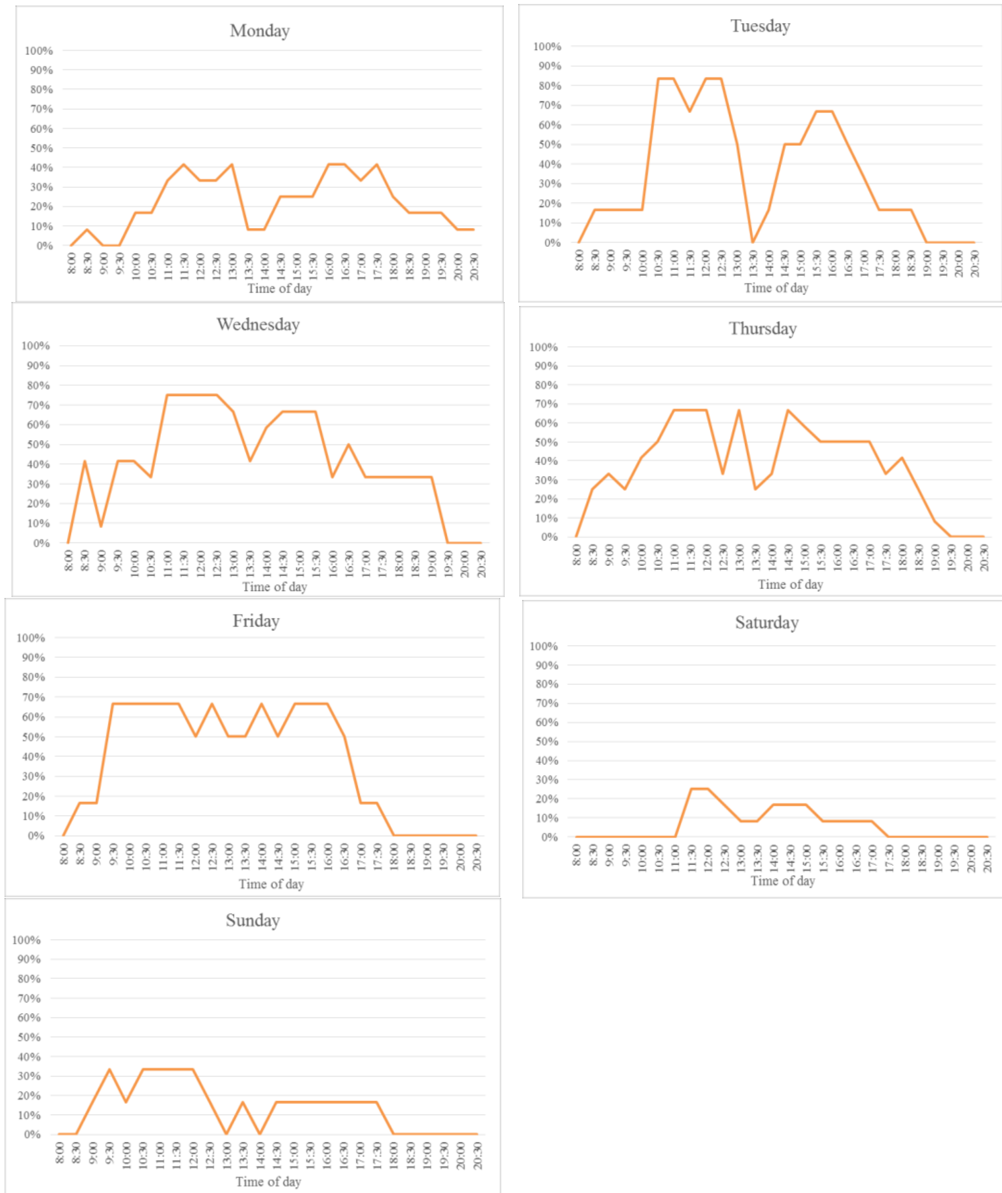


Figure 4-19 Probabilistic profile of Zone 2

4.3.6 Energy Consumption Simulation

A model replicating the area of interest is created in DesignBuilder. To import the obtained probabilistic profile to the simulation model, the profile is rewritten in the format of compact schedule. The occupancy schedule imported to the energy simulation program is displayed in Appendix E.

To verify the energy saving brought by the proposed local control strategy, four scenarios are created, as Table 4-8 shows. For Scenario 1, it is assumed that the occupants work from 8:00 to 20:30. So the setpoint is adjust to 22 ^{0}C within this time and to 26^{0}C for the rest of the day, which is the actual cooling schedule currently applied to the lab. For Scenario 2, the setpoint temperature of the whole space is adjusted to 26^{0}C when there is no occupant, and 22^{0}C during the period of the first arrival and the last departure of all the occupants. For Scenario 3 and 4, the setpoint temperature is adjusted for the two zones respectively according to the presence in the zone. In Scenario 3, the setpoint is 22^{0}C when the occupant in the zone present and 26^{0}C when the zone is not occupied. However, in Scenario 4, the weighted setpoint temperature $\overline{T_Z^{t,d}}$ of each zone is calculated following Equation 3-4 based on the preferences of the occupants, as explained in Section 3.5.2. The cooling schedules of Scenario 2, 3 and 4 are listed in Appendix E.

Table 4-8 Four scenarios of adjustment to the setpoint

Scenario	Cooling schedule	Occupied setpoint(°C)	Unoccupied setpoint(°C)
Scenario 1	8:00 – 20:30	22°C	26°C
Scenario 2	Start: first occupant's arrival End: Last occupant's departure	22°C	26°C
Scenario 3	Local control	22°C	26°C
Scenario 4	Local control	$\overline{T_Z^{t,d}}$	26°C

4.3.7 Energy Simulation Result

Energy consumption simulation is run for one summer (from 1 July to 30 September) to quantify the energy saving brought by the proposed strategy (Scenario 4).

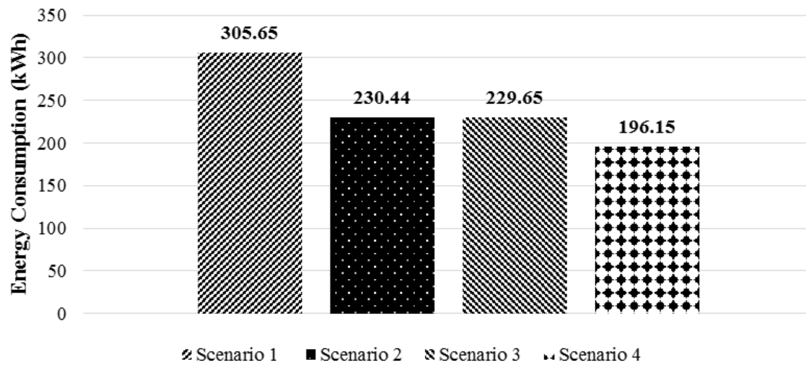


Figure 4-20 Energy simulation results of the four scenarios

Comparing Scenario 4 and Scenario 1, 36% of the energy can be saved. Comparing Scenario 3 and Scenario 4, 15% of the energy is reduced. The considerable amounts of the energy saving result from the fact that half of the occupants sense discomfort and wish for higher setpoints. As shown in Table 4-4, occupants Z, A, and Ns expect 25^{o}C, 24^{o}C, and 24^{o}C, respectively. By contrary, it can be noticed that applying Scenario 3 does not reduce much energy (0.3%) compared with Scenario 2, due to the occupants' presence patterns of the two zones do not differ much. Therefore, the energy saving of the proposed local control strategy based on occupants' locations and preferences depends on the diversity of the schedule among all the zones and the difference of the occupants' preferred setpoints from the fixed setpoints applied in Scenario 1.

4.3.8 Thermal Comfort Discussion

The occupants' thermal discomfort of Scenario 1 and Scenario 4 is analyzed using Equation 2-3 (Salimi, Liu and Hammad, 2017). In this research, instead of applying the equation for different seasons, the time duration of one summer is considered. For Scenario 4, the discomfort level is calculated for all the occupants on each day and averaged for the week, assuming the occupant is present with any probability of presence more than 0%. The results show that for Zone 1, the discomfort level is decreased from 20.3% to 10.2%; For Zone 2, the discomfort level is decreased from 8.3% to 6.1%. The improvement in the thermal comfort in the two zones is caused by the difference between the occupants' preferences and the setpoint of 22ºC in Scenario 1. For example, in Zone 1, according to Table 4-4 two out of three occupants prefer higher than 22ºC (24ºC and 25ºC, respectively). Therefore, there is more satisfaction when the weighted setpoint $\overline{T_{Z}^{t,d}}$ is higher than 22ºC. And for Zone 2, two out of three occupants feel very comfortable with 22ºC. Therefore, if the occupant who prefers 24ºC is present, their discomfort level will increase.

4.4 Sensitivity Analysis -- Case Study 3

4.4.1 Introduction

In case studies 1 and 2, the energy simulation is run with the variations of factors covering building properties, occupancy information and HVAC operation, which are mentioned in Section 3.6.2.

In this case study, 36 cases are generated to quantify the influence of the factors of size of the space, effect of windows, and occupancy density on the proposed local climate control strategy. The values of the factors taken in these cases are shown in Table 4-9. All the combinations of the factors are considered except that when the occupants are assigned randomly, the local control is not applicable.

Table 4-9 Variations of the factors

Building property-related factors	Size of space	200 m^2
		400 m^2
		1000 m^2
	Windows	With
		Without
Occupancy-related factors	Assignment	Random
		Schedule-based
	Density	0.05 person/m^2
		0.1 person/m^2
HVAC operation-related factors	Local control – operation duration	With local control – Based on occupancy presence
		Without local control – 24/7

4.4.2 Energy Consumption Simulation

The occupancy schedule is generated including four patterns, all-day, average-day, short-day, short-day with break, as shown in Table 4-10. The energy simulation is run for a summer design week in Montreal, Canada, which is 13 to 19 July.

According to the proposed local climate control, ideally, one occupant can have the control of one terminal unit as one zone. However, in shared offices, one terminal unit conditions a space with multiple occupants. And for large spaces, one zone can have multiple terminal units. In this case study, it is assumed that the occupants are present in four patterns, as shown in Table 4-10. Therefore, the space is divided into four zones where the occupants are reassigned to these zones based on their schedule.

Table 4-10 Occupancy schedule of four patterns

Group Number	Presence pattern	Presence time
1	All-day	8:00 – 17:00
2	Average-day	8:00 – 16:00
3	Short-day	9:00 –15:00
4	Short-day with break	9:00 – 12:00; 14:00 – 15:00

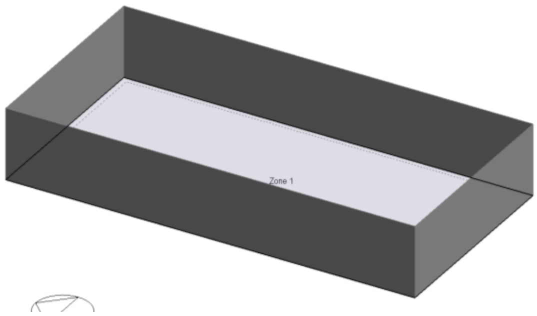
As for the random assignment, the presence time of the occupants is known, but the location of the occupants is not known because the space is not divided into zones. Therefore, the four schedules are combined into time associated with the percentage of the occupancy presence, as shown in Table 4-11.

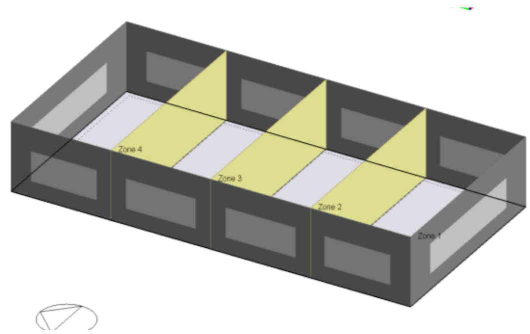
Table 4-11 Combined schedule for random assignment

Time	Percentage of presence
8:00 – 9:00	0.5
9:00 – 12:00	1
12:00 – 14:00	0.75
14:00 – 15:00	1
15:00 – 16:00	0.5
16:00 –17:00	0.25

The HVAC operation setpoint for the cases with random assignment of occupants and the cases without local control is 24 ^{o}C constantly. For the cases with local control, the HVAC setpoint is adjusted to 24 ^{o}C when there is occupant in the zone, and 26^{o}C when there is no occupant in the zone.

Two models of 200 m^2 are shown as examples in Figure 4-21. The model in Figure 4-21 (a) has no window and the proposed control is not applied; the model in Figure 4-21 (a) has windows and the proposed control is applied. Table 4-12 lists all the 36 cases involving the factors mentioned in Section 4.4.1 and the energy simulation results.





(a) Without windows, without local control **(b) With windows, with local control**

Figure 4-21 Energy simulation models

4.4.3 Analysis of the Simulation Results

4.4.3.1 Effect of windows on the building energy consumption

The Window to Wall percentage defined in the cases with windows is 30%. The energy simulation result is shown in Figure 4-22 and the corresponding cases in the groups are shown in Table 4-13.

Comparing the cases with windows and without windows, for example, in Group 1, Case 3 consumes 31.8% more energy because the solar gains through the windows contribute extra heat load to the building. All the cases follow this trend, as shown in Figure 4-22. With the increase in the size, the influence of windows does not vary much. For the sizes of 200 m^2, 400 $m^2$and 1000 m^2, 31.8%, 37.5% and 32% of the energy is reduced when there is no window in the model (Groups 1, 7 and 13).

Table 4-12 Energy consumption of all the cases

Case	Size (m^2)	Assignment	Window	Density (p/m^2)	Local control	Energy Consumption (kWh)
1	200	Random	N	0.1		444.24
2	200	Random	N	0.05		365.91
3	200	Random	Y	0.1		651.58
4	200	Random	Y	0.05		553.13
5	200	Schedule-based	N	0.1	Y	319.51
6	200	Schedule-based	N	0.1	N	402.18
7	200	Schedule-based	N	0.05	Y	298.02
8	200	Schedule-based	N	0.05	N	351.91
9	200	Schedule-based	Y	0.1	Y	565.49
10	200	Schedule-based	Y	0.1	N	656.25
11	200	Schedule-based	Y	0.05	Y	495.29
12	200	Schedule-based	Y	0.05	N	562.89
13	400	Random	N	0.1		1049.02
14	400	Random	N	0.05		867.16
15	400	Random	Y	0.1		1303.13
16	400	Random	Y	0.05		1110.09
17	400	Schedule-based	N	0.1	Y	816.75
18	400	Schedule-based	N	0.1	N	1005.28
19	400	Schedule-based	N	0.05	Y	734.67
20	400	Schedule-based	N	0.05	N	867.90
21	400	Schedule-based	Y	0.1	Y	1151.18
22	400	Schedule-based	Y	0.1	N	1325.51
23	400	Schedule-based	Y	0.05	Y	1016.68
24	400	Schedule-based	Y	0.05	N	1146.44
25	1000	Random	N	0.1		897.83
26	1000	Random	N	0.05		832.09
27	1000	Random	Y	0.1		1321.26
28	1000	Random	Y	0.05		1244.65
29	1000	Schedule-based	N	0.1	Y	692.62
30	1000	Schedule-based	N	0.1	N	927.46
31	1000	Schedule-based	N	0.05	Y	654.26
32	1000	Schedule-based	N	0.05	N	877.52
33	1000	Schedule-based	Y	0.1	Y	1080.40
34	1000	Schedule-based	Y	0.1	N	1312.75
35	1000	Schedule-based	Y	0.05	Y	1037.79
36	1000	Schedule-based	Y	0.05	N	1265.87

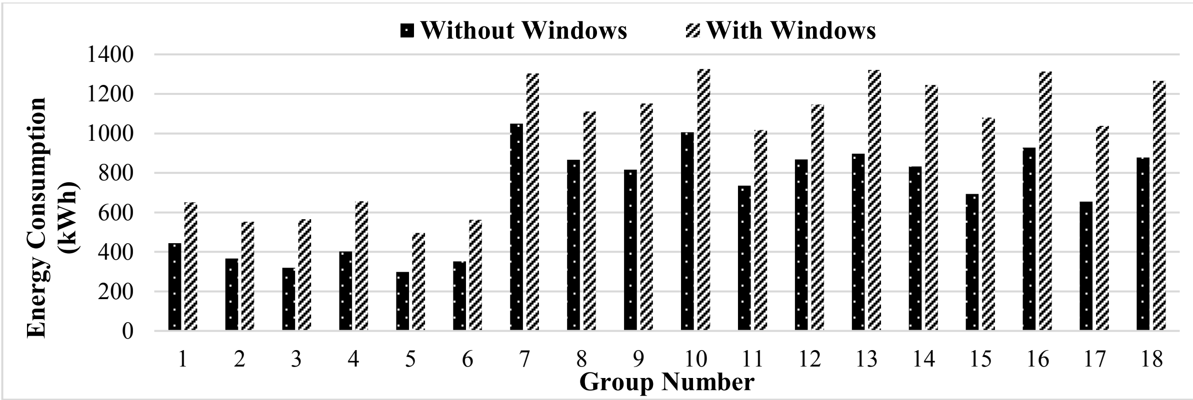


Figure 4-22 Energy consumption comparison regarding effect of windows

Table 4-13 Cases compared within the group for the effect of windows

Group		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Case	N	1	2	5	6	7	8	13	14	17
	Y	3	4	9	10	11	12	15	16	21
Energy Saving		31.8%	33.8%	43.5%	38.7%	39.8%	37.5%	19.5%	21.9%	29.1%
Group		**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Case	N	18	19	20	25	26	29	30	31	32
	Y	22	23	24	27	28	33	34	35	36
Energy Saving		24.2%	27.7%	24.3%	32.0%	33.1%	35.9%	29.3%	37.0%	30.7%

4.4.3.2 Occupancy density effect on the building energy consumption

Comparing the cases with more occupants and less occupants, in Group 1, Case 1 consumes 17.6% more energy because the more occupants, the more metabolism will be added to the heat load in the building. All the cases follow this trend, as shown in Figure 4-23. However, the density of occupancy becomes less influential in the spaces with larger size. For example, for sizes of 200 m^2 and 400 m^2, 17.6% and 17.3% of the energy is reduced when the occupancy changes from 0.1 person/m^2 to 0.05 person/m^2, respectively (Groups 1 and 7), but only 7.3% of the energy is reduced when the density decreases (Group 13) in the model of 1000 m^2.

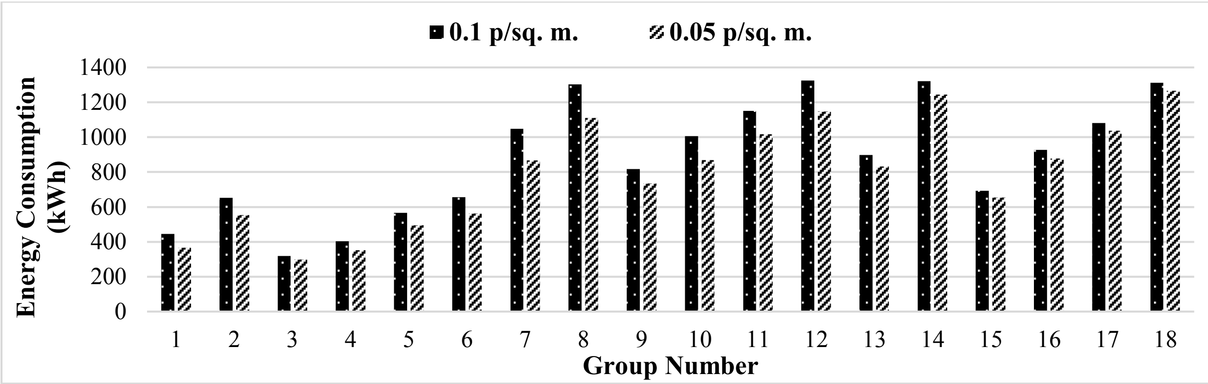


Figure 4-23 Energy consumption comparison regarding occupancy density

Table 4-14 Cases compared within the group for occupancy density

Group		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Case	0.1	1	3	5	6	9	10	13	15	17
	0.05	2	4	7	8	11	12	14	16	19
Energy Saving		17.6%	15.1%	6.7%	12.5%	12.4%	14.2%	17.3%	14.8%	10.0%
Group		**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Case	0.1	18	21	22	25	27	29	30	33	34
	0.05	20	23	24	26	28	31	32	35	36
Energy Saving		13.7%	11.7%	13.5%	7.3%	5.8%	5.5%	5.4%	3.9%	3.6%

4.4.3.3 Energy saving brought by the proposed local control

As shown in Figure 4-24, comparing the cases with and without local control, it can be concluded that the proposed local control can save energy with a percentage of 11.3% (Group 8) to 25.4% (Group 10). The difference in the energy saving is analyzed as followed based on the factors that can affect the building energy consumption.

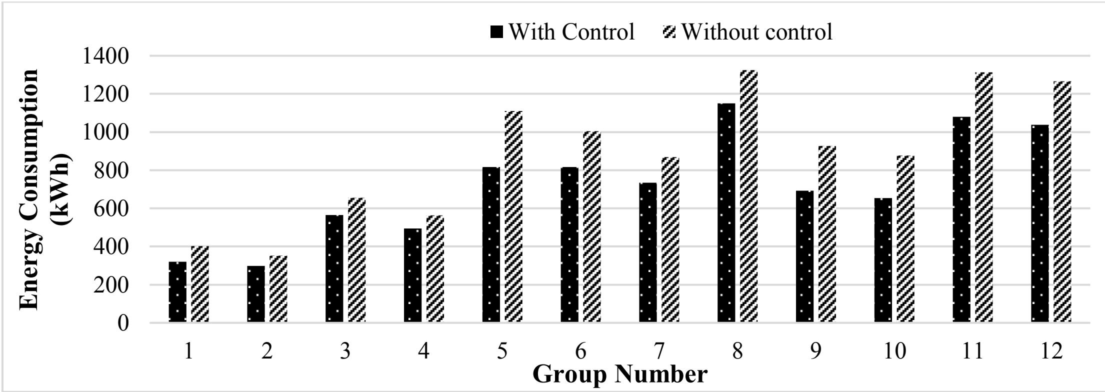


Figure 4-24 Energy consumption comparison regarding the local control

Table 4-15 Cases compared within the group for local control

Group Number		**1**	**2**	**3**	**4**	**5**	**6**
Case	With	5	7	9	11	17	19
	Without	6	8	10	12	18	20
Energy Saving		20.6%	15.3%	13.8%	12.0%	18.8%	15.3%
Group Number		**7**	**8**	**9**	**10**	**11**	**12**
Case	With	21	23	29	31	33	35
	Without	22	24	30	32	34	36
Energy Saving		13.2%	11.3%	25.3%	25.4%	17.7%	18.0%

Factors affecting the effectiveness of the proposed local control:

(1) Size of the space. Comparing the cases of different sizes, the average energy saving of the proposed control can reach 15%, 15%, and 22% for 200 m^2 (Groups 1 to 4), 400 m^2 (Groups 5 to 8), and 1000 m^2 (Groups 9 to 12), respectively. It can be concluded that the proposed control strategy can save more energy in spaces of larger sizes.

(2) Existence of windows. It is found that the cases without windows can reach more energy saving compared with the cases with windows in the space. For example, Group 1(without windows) saves 6.8% more energy compared with Group 3 (with windows). This is because

the windows bring more cooling loads from the solar gains that need to be dealt with. Therefore, the HVAC system consumes more energy to condition the space to reach the setpoint.

(3) Density of occupants. By comparing the cases with denser occupancy and the cases that the space is less occupied, for example, the energy savings of Groups 1 (0.1 p/m^2) and 2 (0.05 p/m^2), it is found that the proposed strategy has better performance with denser occupants.

4.5 Sensitivity Analysis of Local Control Temperature Setpoints

4.5.1 Introduction

To better understand the sensitivity of the local control temperature setpoints, 12 simulation models (the models involving local control) out of 36 cases are studied with the variation of setpoints when the space is occupied / unoccupied.

4.5.2 Assumptions

According to ASHARE 90.1-2007, the recommended range for cooling occupied and unoccupied hours temperature setpoint are 23.9^{o}C – 37.2^{o}C and 37.2^{o}C – 23.9^{o}C, respectively. However, it is not realistic to set the temperature of the regular occupied office to be 30 ^{o}C or higher in summer. Therefore, the range of the occupied hours' setpoints is assumed to be 24^{o}C – 28^{o}C and unoccupied hours' setpoints is assumed to be 24^{o}C – 30^{o}C. In addition, the increment of the setpoint variation is defined as 2^{o}C.

In Case Studies 1 and 2, the temperature setpoints adopted in the local control are 24^{o}C (occupied) and 26^{o}C (unoccupied), which is also included as one case (represented by No.b) for each model in this section. Hence, for each simulation model, 9 cases numbered from $a - i$ with different local control setpoints are discussed. The temperature setpoints of the 9 cases are shown as Table 4-16.

4.5.3 Results and Discussion

After running the simulation, as shown in Table 4-16, the results of 108 models are obtained. The sensitivity influence coefficients (IC) are calculated to quantify the influence of the occupied and unoccupied setpoints.

Table 4-16 Results of sensitivity analysis

Case	No.	Occupied hours' setpoint (^{0}C)	Unoccupied hours' setpoint (^{0}C)	Cooling energy consumption (kWh)
5	a	24	24	402.18
	b	24	26	319.51
	c	24	28	317.89
	d	24	30	317.87
	e	26	26	318.02
	f	26	28	315.91
	g	26	30	315.89
	h	28	28	314.82
	i	28	30	314.10
7	a	24	24	351.91
	b	24	26	298.02
	c	24	28	296.64
	d	24	30	296.64
	e	26	26	296.39
	f	26	28	294.31
	g	26	30	294.31
	h	28	28	293.83
	i	28	30	293.42
9	a	24	24	656.25
	b	24	26	565.49
	c	24	28	470.78
	d	24	30	391.47
	e	26	26	549.75
	f	26	28	464.09
	g	26	30	385.55
	h	28	28	447.98

	i	28	30	376.33
11	a	24	24	562.89
	b	24	26	495.29
	c	24	28	430.27
	d	24	30	364.04
	e	26	26	477.64
	f	26	28	419.45
	g	26	30	359.63
	h	28	28	402.74
	i	28	30	347.62
17	a	24	24	1005.28
	b	24	26	816.75
	c	24	28	635.13
	d	24	30	597.22
	e	26	26	806.89
	f	26	28	631.13
	g	26	30	592.80
	h	28	28	619.58
	i	28	30	582.29
19	a	24	24	867.90
	b	24	26	734.67
	c	24	28	598.73
	d	24	30	568.63
	e	26	26	720.85
	f	26	28	593.35
	g	26	30	563.99
	h	28	28	581.15
	i	28	30	551.68
21	a	24	24	1325.51
	b	24	26	1151.18
	c	24	28	962.74
	d	24	30	794.16
	e	26	26	1128.25
	f	26	28	950.15
	g	26	30	788.28
	h	28	28	925.01
	i	28	30	777.10
23	a	24	24	1146.44
	b	24	26	1016.68
	c	24	28	880.00
	d	24	30	738.32
	e	26	26	992.83
	f	26	28	864.32
	g	26	30	731.49
	h	28	28	837.26
	i	28	30	717.32
29	a	24	24	927.46

	b	24	26	692.62
	c	24	28	581.04
	d	24	30	492.61
	e	26	26	648.23
	f	26	28	523.86
	g	26	30	440.55
	h	28	28	452.39
	i	28	30	375.81
31	a	24	24	877.52
	b	24	26	654.26
	c	24	28	555.98
	d	24	30	468.29
	e	26	26	563.26
	f	26	28	460.94
	g	26	30	398.00
	h	28	28	421.08
	i	28	30	349.05
33	a	24	24	1312.75
	b	24	26	1080.40
	c	24	28	880.41
	d	24	30	747.01
	e	26	26	1087.17
	f	26	28	857.81
	g	26	30	732.91
	h	28	28	830.13
	i	28	30	690.80
35	a	24	24	1265.87
	b	24	26	1037.79
	c	24	28	860.83
	d	24	30	720.55
	e	26	26	1045.00
	f	26	28	822.56
	g	26	30	706.61
	h	28	28	781.23
	i	28	30	640.03

As shown in Table 4-17, the average value of the IC for occupied and unoccupied hours' setpoints are -0.45 and -1.69, respectively. The results mean that the increase in both occupied and unoccupied hours' setpoints will result in a decrease in the building energy consumption, but unoccupied hours' setpoint has more influence on the building energy consumption than occupied hours' setpoint.

Table 4-17 Average IC for different occupied and unoccupied hours' setpoints

	IC for occupied hours' setpoints	IC for unoccupied hours' setpoints
24^0C	-0.41	-1.76
26^0C	-0.56	-1.71
28^0C		-1.60
Average	-0.45	-1.69

To better understand the relationship between occupied and unoccupied hours' setpoints and the energy consumption of buildings of different sizes, the average IC for the 12 models are analyzed as shown in Figure 4-25.

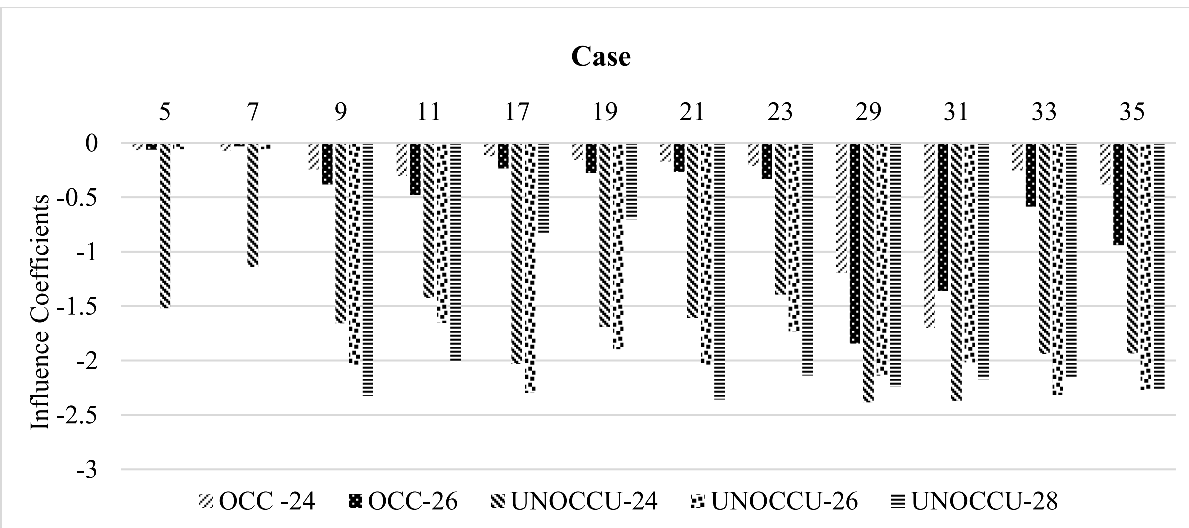


Figure 4-25 Average IC

For example, for OCC-24, occupied hours' setpoint 24^0C is the base case for the calculation of IC. The results of cases with different occupied hours' setpoint and same unoccupied hours' setpoint are compared. Therefore, case *b* (occupied 24^0C – unoccupied 26^0C) is compared with case *e* (occupied 26^0C – unoccupied 26^0C); case *c* (occupied 24^0C – unoccupied 28^0C) is compared with cases *f* (occupied 26^0C – unoccupied 28^0C) and *h* (occupied 28^0C – unoccupied 28^0C); case *d* (occupied 24^0C – unoccupied 30^0C) is compared with cases *g* (occupied 26^0C –

unoccupied 30^0C) and i (occupied 28^0C – unoccupied 30^0C). The average IC for occupied hours' setpoint at 24^0C is calculated by averaging all the ICs based on the above comparisons. The calculation of all the ICs is shown in Appendix G.

The results indicate that in smaller spaces (i.e. Cases 5 to 11), the occupied hours' setpoints have much less influence than in large spaces. However, the unoccupied hours' setpoints show high influence on the energy consumption in most of the cases. Therefore, it is concluded that an efficient way to save energy is to adjust the setpoint to be higher when the space is unoccupied. In addition, it can be concluded that in smaller spaces, changing the setpoint when the space is occupied does not result in a significant change in the energy comsumption (-0.063 for Case 5 and -0.052 for Case 7); However, in larger space, the adjustment in the occupied hours' setpoint can lead to a significant change in the energy consumption (-1.52 for Case 29).

4.6 Summary and Conclusions

In this chapter, three case studies are implemented to investigate the proposed local climate control strategy.

In Case Study 1, the occupancy profiles are generated based on the data collection from a former research using UWB RTLSs. The HVAC system is adjusted based on the occupants' presence in the zones. The energy simulation result shows 13% of energy can be saved.

In Case Study 2, the BLE-based tracking system is used to detect the occupancy presence in the zones after being validated by running two short-term tests. The probabilistic occupancy profiles are generated by processing the output data of the tracking system and are associated with the occupants' preferences. Therefore, the HVAC system operation setpoint temperature is adjusted based on the occupants' locations and preferences. The energy saving and the occupancy discomfort of the proposed local climate control strategy are calculated and analyzed. The energy simulation results indicate that 36% of energy saving can be reached and the occupants' discomfort of Zones1 and 2 can decrease by 10.2% and 2.2%, respectively.

In Case Study 3, the sensitivity analysis of the factors affecting the energy simulation and the HVAC setpoint temperature for the occupied and unoccupied conditions is performed. It is concluded that the proposed control strategy can reach 11.3% to 25.4% energy saving depending on several factors, such as size of the space, with or without windows, and occupancy density. Besides, it is concluded that the unoccupied hours' setpoint has more influence on the energy consumption.

CHAPTER 5 Conclusions, Limitations, and Future Work

5.1 Summary of Research

Reviewing the literature concerning occupancy behavior concluded that by involving the occupancy-related parameters, a great amount of building energy can be saved. But there are few research works involving the locations and preferences of occupants in open offices with multiple users assigned to and controlling the HVAC and lighting system locally at the zone level in the large space, since when there are different occupants with different preferences in specific zones of the space, it is energy-wasting to condition the whole space based on a fixed setpoint.

This research proposes a local climate control strategy in shared offices based on occupants' locations and preferences. Firstly, the open space is divided into zones based on the number of the HVAC terminal units. Then, the occupants' preferences and tracking the occupants' locations at the zone level are collected by occupancy tracking technology. The probabilistic profiles for each zone is generated by processing the output data of the tracking system. Finally, the HVAC setpoint temperature of each terminal unit is adjusted based on the probabilistic profiles for each zone and the preferences of the occupants that are present in the corresponding zone. Three case studies are implemented to quantify the energy saving brought by the local climate control strategy.

In Case Study 1, based on the occupancy presence information from another research using UWB technology, the probabilistic profiles for each zone are generated and imported to the energy simulation tool DesignBuilder to verify the proposed methodology. The energy simulation runs for the summer period. Without knowing the occupants' preferences, the

HVAC system is set to be 24°C when occupied and 26 °C when unoccupied for applying the proposed local climate control. The results show that 13% of the energy can be saved compared with the 24/7 HVAC operation with a constant 24°C setpoint.

In Case Study 2, the preferences of all the occupants are collected. Then, a BLE-based occupancy tracking system is selected due to its low power consuming and the excellent performance for occupancy tracking. By studying the operation for the system, steps of system setup, project design, locator configuration, tag update rate customization and configuration, and data logging customization are followed. The system is validated through short-term tests. After getting the occupancy tracking system ready, a one-month test is run in a graduate laboratory in Concordia University, Canada to capture the occupancy information, (i.e. *Who*, *When* and *Where*). The collected data is analyzed by a data processing program and averaged for an average week data, and the probabilistic profile for each zone is calculated by combining the average week data of all the occupants in the zone. According to the results of simulation, by setting different setpoints based on the occupants' locations and preferences, 36% of the energy can be saved compared with the current operation in the room (22°C when occupied/ 26°C when unoccupied based on general work hours). By analyzing the results, it is concluded that the amount of energy saving brought by the proposed local climate control strategy depends on the diversity of the occupancy presence pattern from zone to zone and the difference between the occupants' preferred setpoint and the fixed setpoint of the system.

Comparing the two simulations, the amount of energy can be saved is different, which is because occupants' preferences are not involved in Case Study 1 and the setpoint of the two case studies are different. However, to explore more factors affecting the energy consumption concerning the control strategy and the sensitivity of the HVAC setpoint, Case Study 3 is implemented. The factors of effect of windows, density of occupancy, size of space are analyzed. Besides, the sensitivity analysis of the occupied and unoccupied hours' setpoints is conducted and it is concluded that the unoccupied hours' setpoint has more influence on the energy consumption and the occupied hours' setpoint has more influence on larger spaces.

5.2 Research Contributions

The contributions of this research are:

(1) The tracking system BLE used in this research is power saving and can be easily installed compared with other systems in the market. The application of BLE in the field of occupancy tracking for evaluating the building energy performance is relatively new.

(2) Local climate control is becoming a frequently discussed topic, but few research involve the occupants' preferences in the control. As shown in the results of Case Study 2, local climate control based on occupants' locations and preferences can serve the purpose to reduce 36% of the energy consumption and improve the occupants' thermal comfort by 10.1% and 2.2% for the two zones, respectively.

(3) The sensitivity analysis of the factors that affect the local climate control such as effect of windows, occupancy density, and size of the space, can be analyzed to understand the effectiveness of the control strategy in different conditions. The results show that the strategy can reach 11.3% (for a space of 400 m^2 with window to wall percentage of 30% and the occupancy density of 0.05 p/m^2) to 25.4% (for a space of 1000 m^2 with no windows and the occupancy density of 0.05 p/m^2) energy savings. The sensitivity analysis

of HVAC setpoint temperature can be very useful in analyzing the influence of occupied and unoccupied setpoint for different sizes of space.

5.3 Limitations and Future Work

(1) In the future, the proposed local control strategy can be applied to the lighting system. The occupants' luminance preferences should be collected for the control. As shown in Figure 5-1, similar to the local climate control, the space is divided into zones based on the number of the lighting units. The luminance level will be adjusted based on the presence and preferences of the occupant(s) in the same zone.

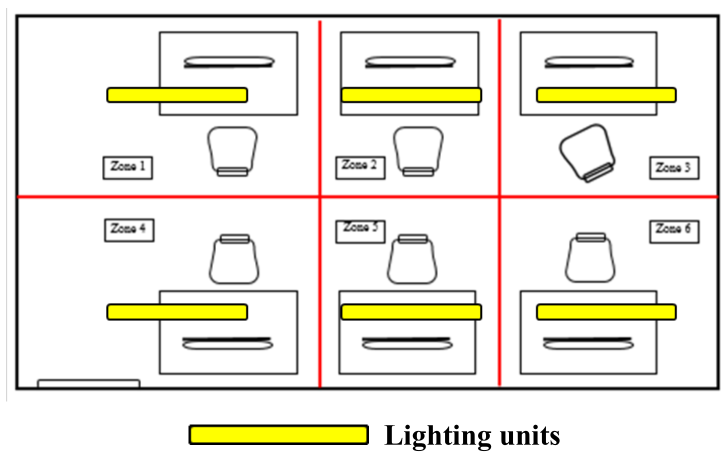


Figure 5-1 Proposed strategy applied to the lighting system

(2) Besides, as mentioned in Section 4.2.5.4, it is much easier to capture and predict the presence pattern of occupants with consistent schedule. However, for the occupants with flexible schedule, long-term data collection is required. Therefore, another limitation of this research is the period of the data collection.

(3) The space is limited and only divided into two zones in Case Studies 1 and 2, which can be improved by conducting the test in the future in a larger space with more zones involved.

(4) During the data collection in the case study, it is noticed that for Zone 1, the occupants prefer 22°C (S), 24°C (A), and 25°C (Z) respectively; for $Zone_2$, the setpoints that occupants feel comfortable with are 22°C (Ng), 22°C (Al), and 24°C (Ns). It can be investigated and discussed whether exchanging S and Ns and making the setpoint of Zone 1 24°C and Zone 2 22 °C will reduce energy consumption as well as satisfy the occupants. Therefore, reassignment of the occupants based on their preferences can be a future topic for the research.

(5) In this research, BLE is selected to track the occupants, and one of its major advantages is that the occupants can be tracked use any device that implements BLE standard. Therefore, in the future, smartphones can be configured as tags to eliminate the hassles brought to the occupants.

(6) Moreover, it is found that the energy saving brought by the local climate control strategy depends on the diversity of the occupancy schedule to a large extent. In the future, the relationship between diversity of schedule and the performance of the proposed strategy can be investigated.

(7) Another future work can be optimizing the HVAC operation parameters using optimization tools, to balance reduction in energy consumption and satisfaction of the occupancy comfort.

REFERENCES

Agarwal, Y., Balaji, B., Gupta, R., Lyles, J., Wei, M. and Weng, T., (2010). Occupancy-driven energy management for smart building automation. Proceedings of the BuildSys, in conjunction with ACM SenSys Conference, Zurich, Switzerland.

Azar, M., and Menassa, C. C., (2012). A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. *Energy and Buildings*, Vol. 55, pp. 841-853.

Azar, M., and Menassa, C. C., (2014). Framework to evaluate energy-saving potential from occupancy interventions in typical commercial buildings in the United States. *Journal of Computing in Civil Engineering*, Vol. 28, No. 1, pp. 63-78.

Bluetooth Specification., (2010). Core Package version 4.0.

Bratt, N., Johansen, C. and Singh, M. P., (2015). Driving forces for energy demand. On-line: http://etreeprojects.com, Accessed: 02/05/2017.

BREEAM. The Edge, Amsterdam, (2015). On-line: http://www.breeam.com/index.jsp?id=804, Accessed: 14/09/2016.

Budaiwi, I., and Abdou. A., (2013). HVAC system operational strategies for reduced energy consumption in buildings with intermittent occupancy: the case of mosques. *Energy conversion and Management*, Vol. 73, pp. 37-50.

Caffrey, J. J., and Stüber, G. L., (1998). Overview of radiolocation in CDMA cellular systems. *IEEE Communications Magazine*, Vol. 36, No. 4, pp. 38–45.

Conte, G., Marchi, M. D., Nacci, A. A., Rana, V., and Sciuto, D., (2014). BlueSentinel: a first approach using iBeacon for an energy efficient occupancy detection system. 1st ACM International Conference on Embedded Systems for Energy-Efficient Buildings (BuildSys).

Curran, K., Furey, E., Lunney, T., Santos, J., Woods, D., and McCaughey, A., (2011). An evaluation of indoor location determination technologies. *Journal of Location Based Services*, Vol. 5, No. 2, pp. 61-78.

Defence Estates, (2001). Building energy management systems. Stationery Office Books.

DesignBuilder. DesignBuilder. On-line: http://www.designbuilder.co.uk/, Accessed: 20/06/2016.

DesignBuilder. DesignBuilder video tutorials, (2015). On-line: https://www.designbuilder.co.uk/training/online-learning/tutorials/, Accessed: 14/10/2016.

DOE, (2011). Building energy data book. US Department of Energy. On-line: https://catalog.data.gov/dataset/buildings-energy-data-book, Accessed: 03/07/2017.

Duong, P. R., (2016). How can occupancy modeling and occupancy sensors reduce energy usage in academic buildings: an application approach to University of San Francisco. *Master's Projects*, Paper 337, San Francisco.

EU-Energy-Star, (2016). EU-Energy-Star database, Energy Calculator. On-line: https://eu-energystar.org/calculator.htm, Accessed: 03/02/2017.

EBC Annex 53, (2016). Total energy use in buildings: analysis and evaluation methods (Annex 53) – project summary report. International Energy Agency.

Feng, X., Yan, D., and Hong, T., (2015). Simulation of occupancy in buildings. *Energy and Buildings*, Vol. 87, pp. 348-359.

Gomez, C., Oller, J., and Paradells, J., (2012). Overview and evaluation of Bluetooth Low Energy: an emerging low-power wireless technology. *Sensors*, Vol. 12, No. 9, pp. 11734-11753.

Grizzly Analytics, (2015). Seeing Quuppa's indoor location technology at MWC 2015. On-line: http://grizzlyanalytics.blogspot.ca/2015/03/seeing-quuppas-indoor-location.html. Accessed: 4/15/2017.

Gunay, H. B., O'Brien, W., and Beausoleil-Morrison, I., (2015). Development of an occupancy learning algorithm for terminal heating and cooling units. *Building and Environment*, Vol. 93, pp. 71-85.

Hightower, J., and Borriello, G., (2001). Location systems for ubiquitous computing. *IEEE Computer*, Vol. 34, pp. 57–66.

HockeyTech, (2017). Tracking the on-ice movements of puck and players. On-line: https://www.hockeytech.com/tracking-analytics/, Accessed: 16/03/2017.

Hong, T., and Lin, H., (2013). Occupant behavior: impact on energy use of private offices. Ernest Orlando Lawrence Berkeley National Laboratory.

Ibeaconinsider, (1995). What is iBeacon? A guide to beacons. On-line: http://www.ibeacon.com/what-is-ibeacon-a-guide-to-beacons/, Accessed: 17/06/2016.

IndustryARC, (2017). Bluetooth Smart/Bluetooth Low Energy market: applications (consumer electronics, healthcare, sports & fitness, retail, automotive, security); by technology [discrete modules, integrated modules (single & dual mode)]-forecast (2017-2022). On-line: http://industryarc.com, Accessed: 04/03/2017.

Khalel, A. M. H., (2010). Position location techniques in wireless communication systems. *Master electrical engineering emphasis on telecommunications*, Blekinge Institute of Technology Karlskrona, Sweden.

Levermore, G. J., (2000). *Building energy management systems: applications to low-energy HVAC and natural ventilation control*. London: E & FN Spon.

Lo, L. J. and Novoselac, A., (2010). Localized air-conditioning with occupancy control in an open office. *Energy and Buildings*, Vol. 42, pp. 1120-1128.

Mackensen, E., Lai, M., and Wendt, T. M., (2012). Performance analysis of a Bluetooth Low Energy sensor system. In Proc. 1st into Symp. *Wireless Syst*. (iDAACS-SWS' 12), pp. 62-66, Offenburg, Germany.

Masoudifar, N., Hammad, A., and Rezaee, M., (2014). Monitoring occupancy and office equipment energy consumption using real-time location system and wireless energy meters. *Proceedings of the 2014 Winter Simulation Conference*, pp. 1108-1119.

Mikhaylov, K., Plevritakis, N., and Tervonen, J., (2013). Performance analysis and comparison of Bluetooth Low Energy with IEEE 802.15.4 and SimpliciTT. *Journal of Sensor and Actuator Networks*, Vol. 2, No. 3, pp. 589-613.

Monfet, D., Charneux, R., Zmeureanu, R., and Lemire, N., (2009). Calibration of a building energy model using measured data. *ASHRAE Transactions*, Vol. 115, No. 1, pp. 348-359.

Murphy, J., and Maldeis, P.E. N., (2009). Using time-of-day scheduling to save energy. *ASHRAE Journal.* Vol. 51, No. 5, pp. 42-49.

NRCan, (2011). 15th edition of energy efficiency trends in Canada. On-line: http;//www.nrcan.gc.ca, Accessed: 12/06/2017.

Parys, W., Saelens, D., and Hens, H., (2009). Impact of occupant behavior on lighting energy use. *Proceedings of Building Simulation*.

Perez-Lombard, L., Ortiz, J., and Pout, C., (2008). A review on buildings energy consumption information. *Energy and Buildings*, Vol. 40, No. 3, pp. 394-398.

Polleti, T., (2015). Can a Google Maps for indoors save shopping malls? On-line: www.marketwatch.com, Accessed: 17/03/2017.

Priyadarshini, R. and Mehra, R. M., (2015). Quantitative review of occupancy detection technologies. *International Journal of Radio Frequency Design*, Vol.1, No. 1, pp. 1-19.

Prosegur, (2015). Prosegur adds Quuppa intelligent locating system to iTrack platform. On-line: https://www.prosegur.com/, Accessed: 12/06/2016.

Quuppa, (2017). Unique technology. On-line: http://quuppa.com/technology/. Accessed: 12/01/2017.

RF Wireless World, (2017). BLE message exchange. On-line: http://www.rfwireless-world.com/Tutorials/Bluetooth-Smart-Bluetooth-Low-Energy-BLE-tutorial.html, Accessed: 4/16/2017.

Roetzel, A., (2015). Occupant behavior simulation for cellular offices in early design stages e Architectural and modelling considerations. *Building Simulation,* Vol. 8, No. 2, pp. 211-224.

Salimi, S., Liu, Z., and Hammad, A., (2017). Simulation-based Optimization of Energy Consumption and Discomfort in Multi-Occupied Offices Considering Occupants Locations and Preferences. *Proceedings of the building simulation 2017 conference.* pp. 1-9.

Spitler, J.D., Fisher, D.E., and Zietlow, D.C, (1989). A primer on the use of influence coefficients in building simulation. *Proceedings of the building simulation'89 conference*. pp. 299–304.

Statler, S., (2016). *Beacon Technologies*: *The Hitchhiker's Guide to the Beacosystem*. California, USA: Apress L. P.

SUSRIS, (2013). International Energy Outlook 2013. On-line: http://susris.com/2013/07/25/international-energy-outlook-2013/, Accessed: 06/06/2017.

Texas instruments, (2016). On-line: http://www.ti.com/, Accessed: 05/12/2016.

Texas Instruments, (2014). SensorTag with iBeacon. On-line: http://processors.wiki.ti.com/index.php/SensorTag_with_iBeacon, Accessed: 05/04/2017.

Turner, C., and Frankel, M., (2008). Energy performance of LEED for new construction buildings. New Buildings Institute.

Wagner, B., and Timmermann, D., (2012). Classification of user positioning techniques and systems for intelligent environments. *GI-Jahrestagung*, Vol. 208, pp. 537-548.

Yan, D., and Hong, T., (2014). IEA EBC Annex 66 Text: Definition and simulation of occupant behavior in buildings. International Energy Agency Energy in Buildings and Communities Program.

Yan, D., O'Brien, W., Hong, T., Feng, X., Burak Gunay, H., Tahmasebi, F., and Mahdavi, A., (2015). Occupant behavior modeling for building performance simulation: current state and future challenges. *Energy and Buildings*, Vol. 107, pp. 264–278.

Yang, Z., and Becerik-Gerber, B., (2014). Coupling occupancy information with HVAC energy simulation: a systematic review of simulation programs. Proceedings of the 2014 Winter Simulation Conference, pp. 3212-3223. Los Angeles, US.

Yang, Z., and Becerik-Gerber, B., (2014). The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use. *Energy and Buildings*, Vol. 78, pp. 113-122.

Yu, B., Xu, L., and Li, Y., (2012). Bluetooth Low Energy (BLE) based mobile electrocardiogram monitoring system. In Proceedings of International Conference on Information and Automation (ICIA'12), Shenyang, China, 6–8 June, 2012; pp. 763–767.

Zhang, J., Lutes, R., Liu, G., and Brambley, M., (2013). Energy savings for occupancy-based control (OBC) of Variable-Air-Volume (VAV) systems. Washington: Pacific Northwest National Laboratory.

Appendix A BLE Enhancement

On the basis of classic Bluetooth, BLE is enhanced in many aspects:

a. Compatibility

There are two types of BLE transceiver chips, single mode and dual mode. Single mode only support BLE; dual mode can support both BLE and classic Bluetooth, which enables the devices with BLE to interoperate with other devices with classic Bluetooth that are already in the market as well as the BLE devices in the future. Therefore, the devices with BLE (laptops, smartphones, etc.) can be easily implemented with wireless sensor networks (Mackensen et al., 2012).

b. Size of protocol stack

The size of the protocol stack is much smaller and less complicated compared with the classic Bluetooth (Gomez et al., 2012).

c. Complexity of link layer state machine

As can be seen in Figure A-1, the logical link layer state machine of BLE for the connection procedure is much simpler than the one of classic Bluetooth. The simplification enables that the messages can be exchanged between BLE devices in 3 ms, significantly faster than classic Bluetooth, which takes 100 ms (RF Wireless World, 2012).

In the state machine, there are five states, but only one state is allowed to be active at a time. In the *Standby* state, it is regarded as low power mode because there is no channel packets transmitted and it can be followed by any one of the other states. A device in the *Advertising* state is called an advertiser, which transmits advertising channel packets and with a possibility of three out of 40, listens and responds to the responses triggered by these advertising channel packets. A device in the *Scanning* state is called a scanner, which listens to the advertising channel packets from other advertisers. A device in the *Initiating* state is called an initiator, which listens to advertising channel packets from certain advertiser(s) and initiates the connection with this or these device(s). A device in the *Connection* state is defined as being in a connection. It can be noticed in Figure A-1 (b) that the device being in a connection can be previously in *Initiating* state or *Advertising* state; for the former condition, the *Connection* state is in the master role. For the latter condition, the *Connection* state is in the slave role. The master role and slave role can communicate with each other. Besides, the master role can define the timings of transmissions of slave role (Bluetooth, 2016).

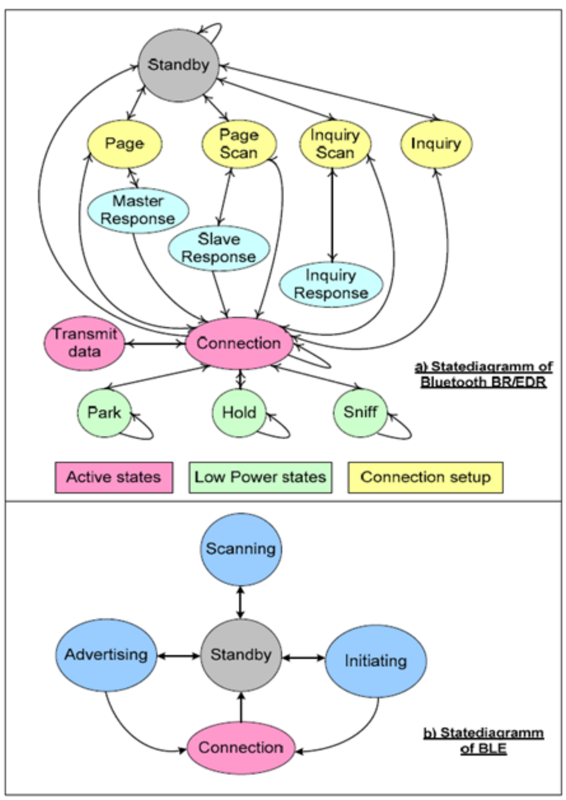
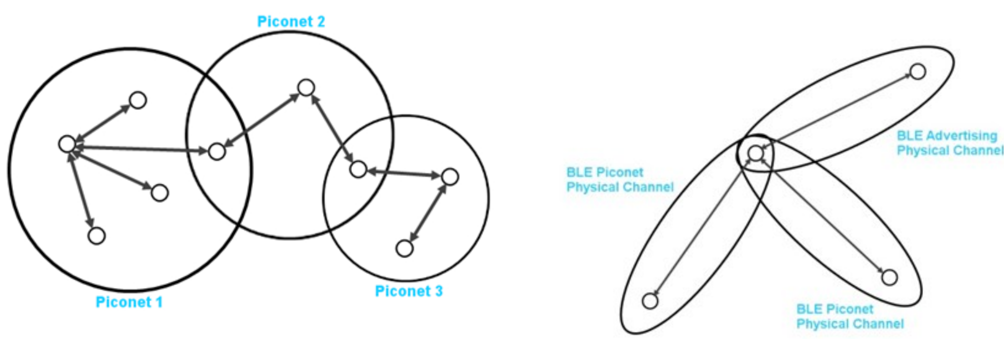


Figure A-1 BLE state machine (Mackensen et al., 2012)

d. Complexity of network structure

The network structure of classic Bluetooth is called *Scatternet* topology. The number of participants in the wireless sensor network of classic Bluetooth is limited to eight because one master can only connect to up to seven slaves within one network of devices, which is called a *piconet*. If more devices need to join the connection, more complex network structures have to be built, as shown in Figure A-2 (a).

However, in BLE, the implementation complexity can be greatly reduced with the adoption of the point-to-point or *Star* topology as can be seen in Figure A-2 (b). Point-to-point connections are used for pairing two devices. As for *Star* topology, the maximum number of participants is 232. It has been proved that Star topology is capable for all the wireless sensor applications (Mackensen et al., 2012).



(a) *Scatternet* topology **(b) *Star* topology**

Figure A-2 Network structures (Mackensen et al., 2012)

e. Data packet length

The data packet length of BLE is 47 bytes, which is much smaller than classic Bluetooth (up to 359 bytes). The deduction in data packet length can avoid delays during transmissions because the larger packets can more possibly result in interference (Mackensen et al., 2012).

Appendix B Quuppa System Configuration User Manual

Label	Locator ID	Concordia Barcode	Condition
01	d0b5c2b94b22	ENCS78974	Good
02	d0b5c2b94902	ENCS78982	Good
03	b4994c5036c4	ENCS78980	Good
04	d0b5c2b94b43	ENCS78977	Good
05	d0b5c2b945af	ENCS78981	Good
06	d0b5c2b944e9	ENCS78979	Good
07	d0b5c2b9472e	ENCS78983	Good
08	b4994c504148	ENCS78976	Good
09	d0b5c2b94b67	ENCS78978	Good
10	d0b5c2b9459d	ENCS78975	Instable signal quality

Table B-1 IDs and labels of the locators

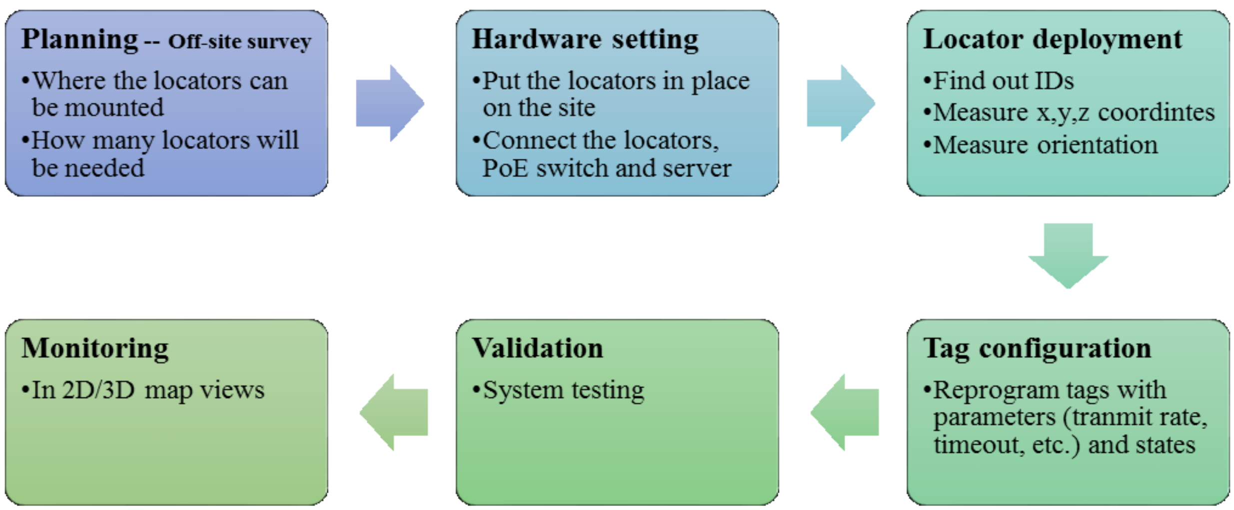


Figure B-1 Typical flow of the configuration

As Table B-1 shows, the locators are labeled for better indicating the ID and signal condition. The typical flow of the configuration of the Quuppa tracking system is shown in Figure B-1. And the steps are explained as follows.

1. Site survey. Measure the dimensions of the area of interest using laser measurement and have a plan of the floor plan in AutoCAD. Make initial plans of the spots to place locators.

2. Physical setup of the system. Connect the display, the keyboard, the mouse and the PoE switch to the Demo Kit computer (the server PC) as shown in Figure B-2 (reference, edited).

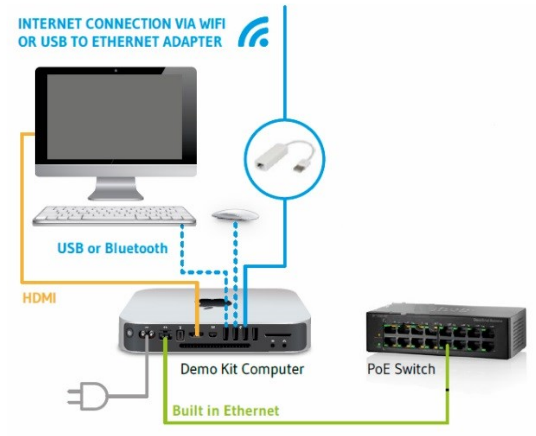


Figure B-2 Connection of the display, the keyboard, the mouse, the PoE switch and the Demo Kit Computer

3. New project. Create a new project in Quuppa Site Planner & Deployer application. Import the floor plan as the background image and georeference the image by defining the dimension in the image with the same one in reality. Add locators and check the adequacy of number by using Render Estimate to see the coverage quality.

4. Installation of locators. Attach the locators to the wood panels and mounting stands using standard ties and steel wires, as shown in Figure B-3. Place the locator kits in the premises according to the plan and connect the locators to the PoE switch.

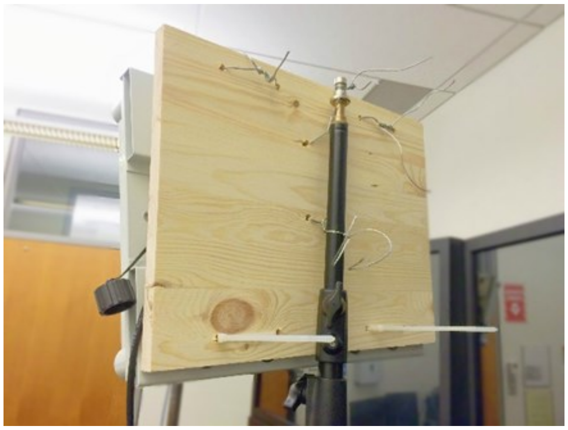
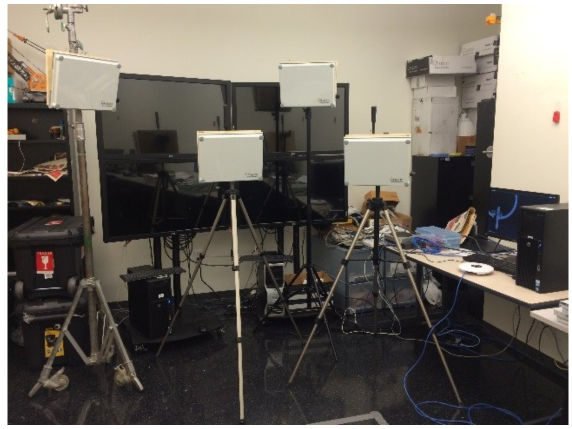
 

Figure B-3 Installation of the locators

5. Location measurement of locators. Use laser measurement to get the accurate locations and heights of the locators. Replicate the numbers in the SPD application to define the position (by coordinates).

6. Identification and focusing of locators. Use focusing locator to identify the ID and orientation of the locators. Note: the focusing locator must be faced to the locators that needs to be identified.

7. Configuration of tags. As shown in Figure B-4, Tag Configuration Editor is used to customize the transmit rate, transmit power and state timeout of Triggered state (when a motion is detected and the transmit rate is very high), Default state (when there is no motion but the tag still sends signal in a lower rate), Temporary state and Storage state (when the tags fall asleep). The tags are activated by press the button on the tags. Move the tags on or near the focusing locators and use Tag Configuration Tool to define the tag name, tag configuration and tag group.

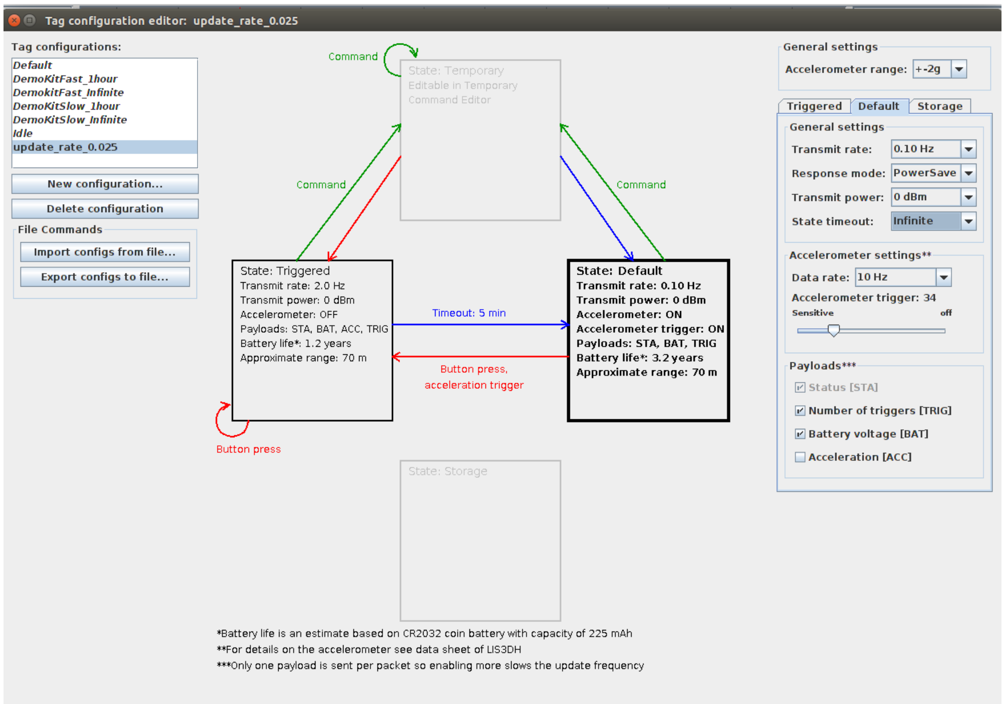


Figure B-4 Tag configuration tool

8. Customizing the output format. Use UDP/logging/API Editor to define a customized output format. For example, as shown in Figure B-5, the CSV format is defined to include the needed information (tag ID, date, time and tag coordinates) following the given commands pattern.

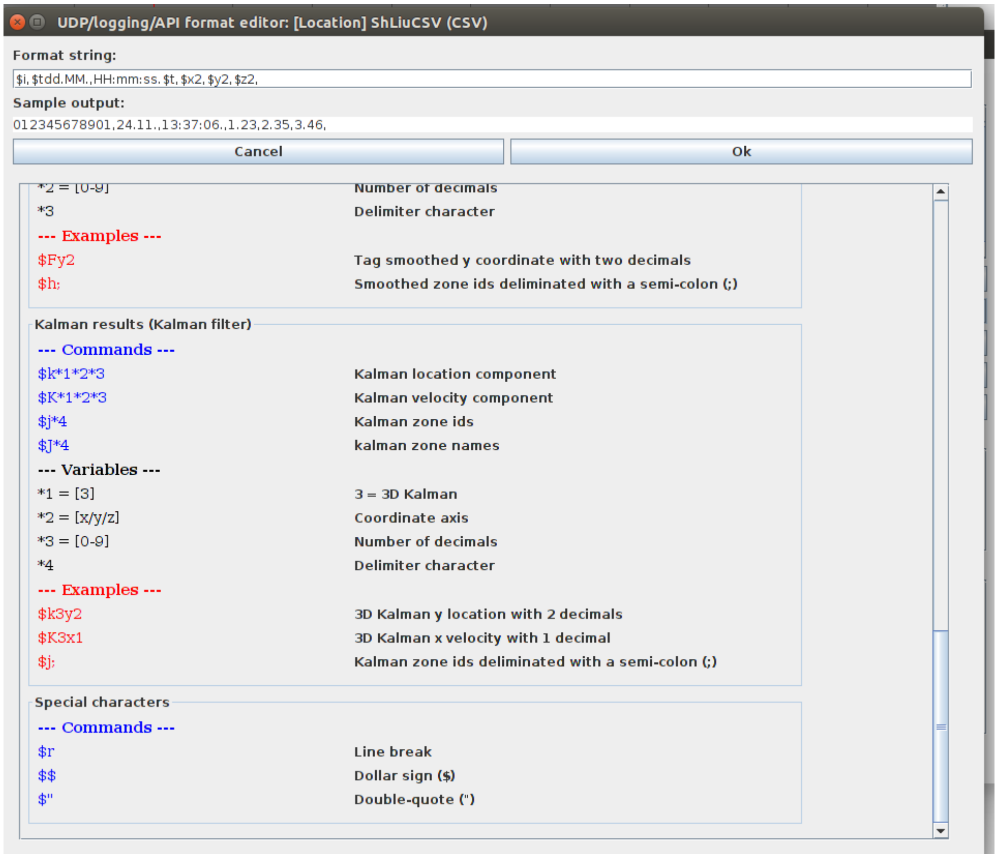


Figure B-5 Example of the UDP/logging/API Editor

9. Project submission. Associate the project with the license and submit.

10. Tracking mode. When the experiment is started, switch on the tag. Start the server and open the Positioning Web Console. The information tables of tags and locators are available on the web console to check the condition and the tags are shown on the 2D and 3D Map Views.

11. Data processing. After running the system, the collected data is available to access in the file created by the UDP/logging/API Editor. The Data Player is also available to replay the data and show the zone history, velocity and etc.

Appendix C Data Processing Program

The data processing program is written in MatLab, which is composed of two parts. The first part is defining the occupants as numbers, serving the purpose to easily deal with the classification of occupants. After dividing the data by occupants, the second part combine the data with continuous time in the same zone for an individual.

Part 1

```
clear all;
clc;
[fileList, folder] = uigetfile('*.xlsx',...
'Find the File to Import', ...
'Multiselect', 'on');

baseFileName = fileList;
fullFileName = fullfile(folder, baseFileName);
[num, txt,all] = xlsread(fullFileName);

first_charactorZheng=strfind(txt(:,1:1),'Zheng');
first_charactorHosein=strfind(txt(:,1:1),'Al-Hosein');
first_charactorAmir=strfind(txt(:,1:1),'Amir');
first_charactorNegar=strfind(txt(:,1:1),'Negar');
first_charactorNeshat=strfind(txt(:,1:1),'Neshat');
first_charactorShide=strfind(txt(:,1:1),'Shide');
first_charactorunknown=strfind(txt(:,1:1),'unknown');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%elemite single
occupents%%%%%%%%%

for a=1:size(first_charactorZheng,1)
   if first_charactorZheng{a}==[1];
      first_charactornumZheng(a)=1;
   else
```

```
        first_charactornumZheng(a)=0;
    end
end
numZheng=[first_charactornumZheng' num];
b=0;
condition=numZheng(:,1)==b;
numZheng(condition,:)=[];%elimite occupant
locationZheng=numZheng(:,end);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for a=1:size(first_charactorHosein,1)
    if first_charactorHosein{a}==[1];
        first_charactornumHosein(a)=2;
    else
        first_charactornumHosein(a)=0;
    end
end
numHosein=[first_charactornumHosein' num];
b=0;
condition=numHosein(:,1)==b;
numHosein(condition,:)=[];%elimite occupant
locationHosein=numHosein(:,end);
for a=1:size(first_charactorAmir,1)
    if first_charactorAmir{a}==[1];
        first_charactornumAmir(a)=3;
    else
        first_charactornumAmir(a)=0;
    end
end
numAmir=[first_charactornumAmir' num];
b=0;
condition=numAmir(:,1)==b;
numAmir(condition,:)=[];%elimite occupant
locationAmir=numAmir(:,end);
```

```
for a=1:size(first_charactorNegar,1)
   if first_charactorNegar{a}==[1];
      first_charactornumNegar(a)=4;
   else
      first_charactornumNegar(a)=0;
   end
end
numNegar=[first_charactornumNegar' num];
b=0;
condition=numNegar(:,1)==b;
numNegar(condition,:)=[];%elimite occupant
locationNegar=numNegar(:,end);
for a=1:size(first_charactorNeshat,1)
   if first_charactorNeshat{a}==[1];
      first_charactornumNeshat(a)=5;
   else
      first_charactornumNeshat(a)=0;
   end
end
numNeshat=[first_charactornumNeshat' num];
b=0;
condition=numNeshat(:,1)==b;
numNeshat(condition,:)=[];%elimite occupant
locationNeshat=numNeshat(:,end);
for a=1:size(first_charactorShide,1)
   if first_charactorShide{a}==[1];
      first_charactornumShide(a)=6;
   else
      first_charactornumShide(a)=0;
   end
end
numShide=[first_charactornumShide' num];
b=0;
```

```
condition=numShide(:,1)==b;
numShide(condition,:)=[];%elimite occupant
locationShide=numShide(:,end);
for a=1:size(first_charactorunknown,1)
   if first_charactorunknown{a}==[1];
      first_charactornumunknown(a)=7;
   else
      first_charactornumunknown(a)=0;
   end
end
numunknown=[first_charactornumunknown' num];
b=0;
condition=numunknown(:,1)==b;
numunknown(condition,:)=[];%elimite occupant
locationunknown=numunknown(:,end);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%fi
nal data processing%%%%%
if size(numZheng,1)==0;
   disp('Zheng is absent');
else
   zhengzone=zone(numZheng, locationZheng);
   filename = 'zhengzone.xlsx';
   xlswrite(filename,zhengzone);
end
if size(numHosein,1)==0;
   disp('Hosein is absent');
else
   Hoseinzone=zone(numHosein,locationHosein);
   filename = 'Hoseinzone.xlsx';
   xlswrite(filename,Hoseinzone);
end
if size(numAmir,1)==0;
   disp('Amir is absent');
else
```

```
  Amirzone=zone(numAmir,locationAmir);
  filename = 'Amirzone.xlsx';
  xlswrite(filename,Amirzone);
end
if size(numNegar,1)==0;
   disp('Negar is absent');
else
  Negarzone=zone(numNegar,locationNegar);
  filename = 'Negarzone.xlsx';
  xlswrite(filename,Negarzone);
end
if size(numNeshat,1)==0;
  disp('Neshat is absent');
else
  Neshatzone=zone(numNeshat,locationNeshat);
  filename = 'Neshatzone.xlsx';
  xlswrite(filename,Neshatzone);
end
if size(numShide,1)==0;
   disp('Shide is absent');
else
   Shidezone=zone(numShide,locationShide);
   filename = 'Shidezone.xlsx';
   xlswrite(filename,Shidezone);
end
if size(numunknown,1)==0;
   disp('unknown is absent');
else
   unknownzone=zone(numunknown,locationunknown);
   filename = 'unknownzone.xlsx';
   xlswrite(filename,unknownzone);
end
```

Part 2

```
function [ B ] = zone( people, location )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here
b=1;
for a=1:size(people,1);
    if a==1;
        B(1,:)=people(1,:);
        b=b+1;
    else
        if     a<=size(people,1)-1;
               if location(a)~=location(a+1);
               B(b,:)=people(a,:);
               b=b+1;
               B(b,:)=people(a+1,:);
               b=b+1;
               else
                 if location(a)==location(a+1);
                    B(b,:)=people(a+1,:);
                 else
                    B(b,:)=people(a,:);
                    B(b+1,:)=people(a+1,:);
                 end

              end
          end
       end
end
```

Appendix D Validation of the Data Processing Program

To validate the occupancy daily profile exported from the data processing program, the comparison between the ground truth and the profile from 1 to 6 of May is made. Note that sometimes the occupants forget to sign in the chart so there are some missing information. The data marked in gray is checked and the gap is caused by the short stay of the occupant.

Table D-1 Validation of the data processing

Date	Occupant	Arrival	Start (profile)	Departure	End (profile)
5.01	Ng	8:30	11:13	18:15	18:10
	A	9:30	10:04	18:15	18:20
	S	11:30	12:06	18:15	18:20
	Ns		15:53	18:15	18:19
5.02	Ng	8:30	10:17	19:00	18:36
	A	10:00	10:10		11:47
	Ns	10:00	10:46	17:00	16:42
5.03	Ng	8:15	8:35	19:30	19:25
	A	9:30	9:38	23:00	22:47
	S	10:45	14:56	19:30	19:28
	Ns	10:30	10:43		16:28
5.04	Ng	8:30	8:25		19:28
	A	8:45	8:57		15:07
	S	9:45	13:18	17:45	17:57
	Ns	10:30	10:51	18:30	15:20
5.05	Ng	8:00	8:02	19:00	18:50
	A	10:30	10:43		15:47
	S	10:45	10:48	10:45	10:48
5.06	Ng	11:15	11:20	16:00	15:35
	A	10:45	10:58		12:16
	Al	11:30	11:44	17:30	17:31

Appendix E Occupancy and HVAC Operation Schedules for the Energy Consumption Simulation

In Case Study 2, the probabilistic profile for the two zones is imported to the energy simulation to reflect the occupancy schedule, which is shown in Figure E-1 and E-2.

```
Schedule:Compact,
Office_Z1,
Fraction,
Through: 31 Dec,
For: Monday,
Until: 9:30, 0,
Until: 10:00, 0.08,
Until: 11:00, 0.42,
Until: 11:30, 0.50,
Until: 12:00, 0.58,
Until: 12:30, 0.50,
Until: 13:00, 0.42,
Until: 13:30, 0.33,
Until: 14:00, 0.17,
Until: 15:00, 0.33,
Until: 15:30, 0.17,
Until: 16:00, 0.25,
Until: 18:00, 0.33,
Until: 18:30, 0.25,
Until: 19:30, 0.08,
Until: 24:00, 0,
For: Tuesday,
Until: 8:00, 0,
Until: 9:00, 0.17,
Until: 9:30, 0.50,
Until: 10:30, 0.33,
Until: 11:00, 0.50,
Until: 11:30, 0.83,
Until: 12:00, 0.67,
Until: 12:30, 0.67,
Until: 13:00, 0.50,
Until: 13:30, 0.17,
Until: 14:00, 0.33,
Until: 14:30, 0.50,
Until: 15:30, 0.67,
Until: 18:00, 0.50,
Until: 24:00, 0,
For: Wednesday,
Until: 8:00, 0,
Until: 9:30, 0.33,
Until: 10:00, 0.50,
Until: 10:30, 0.33,
Until: 11:00, 0.50,
Until: 12:30, 0.67,
Until: 13:00, 0.50,
Until: 13:30, 0.33,
Until: 14:00, 0.67,
Until: 14:30, 0.50,
Until: 15:00, 0.83,
Until: 15:30, 0.67,
Until: 16:00, 0.50,
Until: 17:30, 0.67,
Until: 18:00, 0.33,
Until: 19:00, 0.17,
Until: 24:00, 0,
For: Thursday,
Until: 8:30, 0,
Until: 9:00, 0.17,
Until: 9:30, 0.25,
Until: 10:30, 0.42,
Until: 11:00, 0.33,
Until: 11:30, 0.67,
Until: 12:00, 0.58,
Until: 13:00, 0.67,
Until: 13:30, 0.33,
Until: 14:30, 1,
Until: 15:00, 0.92,
Until: 15:30, 0.58,
Until: 16:00, 0.75,
Until: 17:30, 0.67,
Until: 18:00, 0.50,
Until: 19:30, 0.17,
Until: 24:00, 0,
For: Friday,
Until: 8:00, 0,
Until: 10:00, 0.08,
Until: 10:30, 0.17,
Until: 11:00, 0.92,
Until: 11:30, 0.50,
Until: 12:00, 0.33,
Until: 13:00, 0.83,
Until: 14:00, 0.50,
Until: 15:00, 0.67,
Until: 15:30, 0.75,
Until: 16:00, 0.50,
Until: 18:00, 0.17,
Until: 24:00, 0,
For: Saturday,
Until: 10:30, 0,
Until: 14:30, 0.08,
Until: 24:00, 0,
For: Sunday,
Until: 24:00, 0,
For:  AllOtherDays,
Until: 24:00, 0;
```

Figure E-1 Occupancy schedule of Zone 1

```
Schedule:Compact,
Office_Z2,
Fraction,
Through: 31 Dec,
For: Monday,
Until: 8:00, 0,
Until: 8:30, 0.08,
Until: 9:30, 0,
Until: 10:30, 0.17,
Until: 11:00, 0.33,
Until: 11:30, 0.42,
Until: 12:30, 0.33,
Until: 13:00, 0.42,
Until: 14:00, 0.08,
Until: 15:30, 0.25,
Until: 16:30, 0.42,
Until: 17:00, 0.33,
Until: 17:30, 0.50,
Until: 18:00, 0.25,
Until: 19:30, 0.17,
Until: 20:30, 0.08,
Until: 24:00, 0,
For: Tuesday,
Until: 8:00, 0,
Until: 10:00, 0.17,
Until: 11:00, 0.83,
Until: 11:30, 0.67,
Until: 12:30, 0.83,
Until: 13:00, 0.50,
Until: 13:30, 0,
Until: 14:00, 0.17,
Until: 15:00, 0.50,
Until: 16:00, 0.67,
Until: 16:30, 0.50,
Until: 17:00, 0.33,
Until: 18:30, 0.17,
Until: 24:00, 0,
For: Wednesday,
Until: 8:00, 0,
Until: 8:30, 0.42,
Until: 9:00, 0.08,
Until: 9:30, 0.42,
Until: 10:00, 0.42,
Until: 10:30, 0.33,
Until: 12:30, 0.75,
Until: 13:00, 0.67,
Until: 13:30, 0.42,
Until: 14:00, 0.58,
Until: 15:30, 0.67,
Until: 16:00, 0.33,
Until: 16:30, 0.50,
Until: 19:00, 0.33,
Until: 24:00, 0,
For: Thursday,
Until: 8:00, 0,
Until: 8:30, 0.25,
Until: 9:00, 0.33,
Until: 9:30, 0.25,
Until: 10:00, 0.42,
Until: 10:30, 0.50,
Until: 12:00, 0.67,
Until: 12:30, 0.33,
Until: 13:00, 0.67,
Until: 13:30, 0.25,
Until: 14:00, 0.33,
Until: 14:30, 0.67,
Until: 15:00, 0.58,
Until: 17:00, 0.50,
Until: 17:30, 0.33,
Until: 18:00, 0.42,
Until: 18:30, 0.25,
Until: 19:00, 0.08,
Until: 24:00, 0,
For: Friday,
Until: 7:30, 0,
Until: 8:00, 0.08,
Until: 8:30, 0.25,
Until: 9:00, 0.17,
Until: 11:30, 0.67,
Until: 12:00, 0.50,
Until: 12:30, 0.67,
Until: 13:30, 0.50,
Until: 14:00, 0.67,
Until: 14:30, 0.50,
Until: 16:00, 0.67,
Until: 16:30, 0.50,
Until: 17:30, 0.17,
Until: 24:00, 0,
For: Saturday,
Until: 11:00, 0,
Until: 12:00, 0.25,
Until: 12:30, 0.17,
Until: 13:30, 0.08,
Until: 15:00, 0.17,
Until: 17:00, 0.08,
Until: 24:00, 0,
For: Sunday,
Until: 8:30, 0,
Until: 9:00, 0.17,
Until: 9:30, 0.33,
Until: 10:00, 0.17,
Until: 12:00, 0.33,
Until: 12:30, 0.17,
Until: 13:00, 0,
Until: 13:30, 0.17,
Until: 14:00, 0,
Until: 17:30, 0.17,
Until: 24:00, 0,
For: AllOtherDays,
Until: 24:00, 0;
```

Figure E-2 Occupancy schedule of Zone 2

As mentioned in 4.4.7, four scenarios are created for the energy consumption simulation to quantify the energy saving brought by the proposed strategy. The cooling schedules of the HVAC system in in Scenario 2 and Scenarios 3 and 4 are listed in the following figures.

```
Schedule:Compact,
On,
Any Number,
Through: 31 Dec,
For: Monday,
Until: 8:00,   26 ,
Until: 8:30,   22 ,
Until: 9:30,   26 ,
Until: 20:30,   22 ,
Until: 24:00,   26 ,
For: Tuesday,
Until: 8:00,   26 ,
Until: 18:30,   22 ,
Until: 24:00,   26 ,
For: Wednesday,
Until: 8:00,   26 ,
Until: 19:00,   22,
Until: 24:00,   26 ,
For: Thursday,
Until: 8:30,   26 ,
Until: 19:30,   22 ,
Until: 24:00,   26 ,
For: Friday,
Until: 7:30,   26 ,
Until: 18:00,   22 ,
Until: 24:00,   26 ,
For: Saturday,
Until: 10:30,   26 ,
Until: 17:00,   22 ,
Until: 24:00,   26 ,
For: Sunday,
Until: 8:30,   26 ,
Until: 12:30,   22 ,
Until: 13:00,   26 ,
Until: 13:30,   22 ,
Until: 14:00,   26 ,
Until: 17:30,   22 ,
Until: 24:00,   26 ,
For: AllOtherDays,
Until: 24:00,   26 ;
```

Figure E-3 Cooling schedule of Scenario 2

```
Schedule:Compact,
On,
Any Number,
Through: 31 Dec,
For: Monday,
Until: 8:30,   26 ,
Until: 19:30,   22 ,
Until: 24:00,   26 ,
For: Tuesday,
Until: 8:00,   26 ,
Until: 18:00,   22 ,
Until: 24:00,   26 ,
For: Wednesday,
Until: 9:30,   26 ,
Until: 10:00,   22 ,
Until: 10:30,   26 ,
Until: 14:30,   22 ,
Until: 24:00,   26 ,
For: Thursday,
Until: 24:00,   26 ,
For: Friday,
Until: 9:30,   26 ,
Until: 19:30,   22 ,
Until: 24:00,   26 ,
For: Saturday,
Until: 8:00,   26 ,
Until: 18:00,   22 ,
Until: 24:00,   26 ,
For: Sunday,
Until: 8:00,   26 ,
Until: 19:00,   22 ,
Until: 24:00,   26 ,
For: AllOtherDays,
Until: 24:00,   26 ;
```

Figure E-4 Cooling schedule of Zone 1 for Scenario 3

Schedule:Compact,	For: Thursday,
On,	Until: 8:00, 26 ,
Any Number,	Until: 19:00, 22 ,
Through: 31 Dec,	Until: 24:00, 26 ,
For: Monday,	For: Friday,
Until: 8:00, 26,	Until: 7:30, 26 ,
Until: 8:30, 22 ,	Until: 17:30, 22 ,
Until: 9:00, 26 ,	Until: 24:00, 26 ,
Until: 20:30, 24,	For: Saturday,
Until: 24:00, 26,	Until: 11:00, 26 ,
For: Tuesday,	Until: 17:00, 22 ,
Until: 8:00, 26,	Until: 24:00, 26 ,
Until: 13:00, 22 ,	For: Sunday,
Until: 13:30, 26 ,	Until: 8:30, 26 ,
Until: 18:30, 22,	Until: 12:30, 22 ,
Until: 24:00, 26,	Until: 13:00, 26 ,
For: Wednesday,	Until: 13:30, 22 ,
Until: 8:00, 26 ,	Until: 17:30, 22,
Until: 19:00, 22 ,	Until: 24:00, 26 ,
Until: 24:00, 26 ,	For: AllOtherDays,
	Until: 24:00, 26 ;

Figure E-5 Cooling schedule of Zone 2 for Scenario 3

Schedule:Compact,
On,
Any Number,
Through: 31 Dec,
For: Monday,
Until: 9:30, 26.00 ,
Until: 10:00, 24.00 ,
Until: 11:00, 23.60 ,
Until: 11:30, 23.33 ,
Until: 12:00, 23.29 ,
Until: 12:30, 23.00 ,
Until: 13:00, 23.40 ,
Until: 13:30, 23.75 ,
Until: 14:00, 24.50 ,
Until: 15:00, 23.25 ,
Until: 15:30, 23.50 ,
Until: 16:00, 23.00 ,
Until: 16:30, 22.75 ,
Until: 17:00, 23.25 ,
Until: 17:30, 22.50 ,
Until: 18:00, 23.00 ,
Until: 18:30, 23.33 ,
Until: 19:30, 22.00 ,
Until: 24:00, 26.00 ,
For: Tuesday,
Until: 8:00, 26.00 ,
Until: 9:00, 24.00 ,
Until: 9:30, 23.33 ,
Until: 10:30, 24.00 ,
Until: 11:00, 23.33 ,
Until: 11:30, 24.00 ,
Until: 12:30, 24.50 ,
Until: 13:30, 24.00 ,
Until: 14:00, 23.00 ,
Until: 14:30, 23.67 ,
Until: 15:30, 24.00 ,
Until: 16:00, 23.67 ,
Until: 18:00, 24.00 ,
Until: 24:00, 26.00 ,
For: Wednesday,
Until: 8:00, 26.00 ,
Until: 9:30, 24.00 ,
Until: 10:00, 23.33 ,
Until: 10:30, 23.00 ,
Until: 11:00, 23.33 ,
Until: 12:30, 23.75 ,
Until: 13:00, 23.67 ,
Until: 13:30, 24.00 ,
Until: 14:00, 23.75 ,
Until: 14:30, 23.67 ,
Until: 15:00, 23.60 ,
Until: 15:30, 23.50 ,
Until: 16:00, 24.00 ,
Until: 18:00, 23.50 ,
Until: 19:00, 22.00 ,
Until: 24:00, 26.00 ,
For: Thursday,
Until: 8:30, 26.00 ,
Until: 9:30, 24.00 ,
Until: 10:30, 23.20 ,
Until: 11:00, 23.00 ,
Until: 11:30, 24.00 ,
Until: 12:00, 24.57 ,
Until: 12:30, 24.50 ,
Until: 13:30, 23.00 ,
Until: 14:30, 23.67 ,
Until: 15:00, 23.64 ,
Until: 15:30, 24.00 ,
Until: 16:00, 23.56 ,
Until: 17:30, 23.50 ,
Until: 18:00, 24.00 ,
Until: 19:30, 22.00 ,
Until: 24:00, 26.00 ,
For: Friday,
Until: 8:00, 26.00 ,
Until: 10:30, 24.00 ,
Until: 11:00, 23.64 ,
Until: 11:30, 23.50 ,
Until: 12:00, 24.25 ,
Until: 12:30, 24.00 ,
Until: 13:00, 23.60 ,
Until: 13:30, 24.67 ,
Until: 14:00, 23.33 ,
Until: 15:00, 24.00 ,
Until: 15:30, 23.56 ,
Until: 16:00, 24.00 ,
Until: 18:00, 22.00 ,
Until: 24:00, 26.00,
For: Saturday,
Until: 9:30, 26.00 ,
Until: 10:00, 24.00 ,
Until: 10:30, 26.00 ,
Until: 14:30, 24.00 ,
Until: 24:00, 26.00 ,
For: Sunday,
Until: 24:00, 26.00 ,
For: AllOtherDays,
Until: 24:00, 26.00 ;

Figure E-6 Cooling schedule of Zone 1 for Scenario 4

```
Schedule:Compact,
On,
Any Number,
Through: 31 Dec,
For: Monday,
Until: 8:00,   26.00 ,
Until: 8:30,   22.00 ,
Until: 9:30,   26.00 ,
Until: 10:00,   22.00 ,
Until: 10:30,   23.00 ,
Until: 11:00,   22.50 ,
Until: 11:30,   22.40 ,
Until: 12:00,   22.50 ,
Until: 12:30,   22.00 ,
Until: 13:00,   22.40 ,
Until: 14:00,   24.00 ,
Until: 15:30,   22.67 ,
Until: 16:30,   22.80 ,
Until: 17:30,   23.00 ,
Until: 18:00,   23.33 ,
Until: 19:30,   23.00 ,
Until: 24:00,   24.00 ,
For: Tuesday,
Until: 8:00,   26.00 ,
Until: 10:00,   22.00 ,
Until: 11:00,   22.80 ,
Until: 11:30,   23.00 ,
Until: 12:30,   22.80 ,
Until: 13:00,   22.67 ,
Until: 13:30,   26.00 ,
Until: 14:00,   22.00 ,
Until: 15:00,   22.67 ,
Until: 16:00,   22.50 ,
Until: 16:30,   22.67 ,
Until: 17:00,   23.00 ,
Until: 18:30,   22.00 ,
Until: 20:00,   26.00 ,
For: Wednesday,
Until: 8:00,   26.00 ,
Until: 10:30,   22.00 ,
Until: 12:30,   22.89 ,
Until: 13:00,   23.00 ,
Until: 13:30,   22.80 ,
Until: 14:00,   23.14 ,
Until: 15:30,   23.00 ,
Until: 16:00,   22.00 ,
Until: 16:30,   23.33 ,
Until: 17:30,   23.00 ,
Until: 19:00,   22.00 ,
Until: 24:00,   26.00 ,
For: Thursday,
Until: 8:00,   26.00 ,
Until: 9:00,   22.00 ,
Until: 9:30,   23.33 ,
Until: 10:00,   22.80 ,
Until: 10:30,   22.67 ,
Until: 12:00,   23.00 ,
Until: 12:30,   22.00 ,
Until: 13:00,   23.00 ,
Until: 13:30,   23.33 ,
Until: 14:30,   23.00 ,
Until: 15:00,   23.14 ,
Until: 17:00,   22.67 ,
Until: 17:30,   23.00 ,
Until: 18:00,   22.80 ,
Until: 18:30,   23.33 ,
Until: 19:00,   22.00 ,
Until: 24:00,   26.00 ,
For: Friday,
Until: 7:30,   26.00 ,
Until: 13:30,   22.00 ,
Until: 14:00,   22.50 ,
Until: 14:30,   22.67 ,
Until: 16:00,   22.50 ,
Until: 16:30,   22.67 ,
Until: 17:30,   24.00 ,
Until: 24:00,   26.00 ,
For: Saturday,
Until: 11:00,   26.00 ,
Until: 17:00,   22.00 ,
Until: 24:00,   26.00 ,
For: Sunday,
Until: 8:30,   26.00 ,
Until: 12:30,   22.00 ,
Until: 13:00,   26.00 ,
Until: 13:30,   22.00 ,
Until: 14:00,   26.00 ,
Until: 17:30,   22.00 ,
Until: 24:00,   26.00 ,
For: AllOtherDays,
Until: 24:00,   26.00 ;
```

Figure E-7 Cooling schedule of Zone 2 for Scenario 4

Appendix F Size of the Collected Data

The size of the collected data is shown in Figure F-1. The occupation of the space can be obtained by comparing the data size of weekdays and weekends. It can be concluded that for weekdays, the occupants are much more possible to present than for weekends.

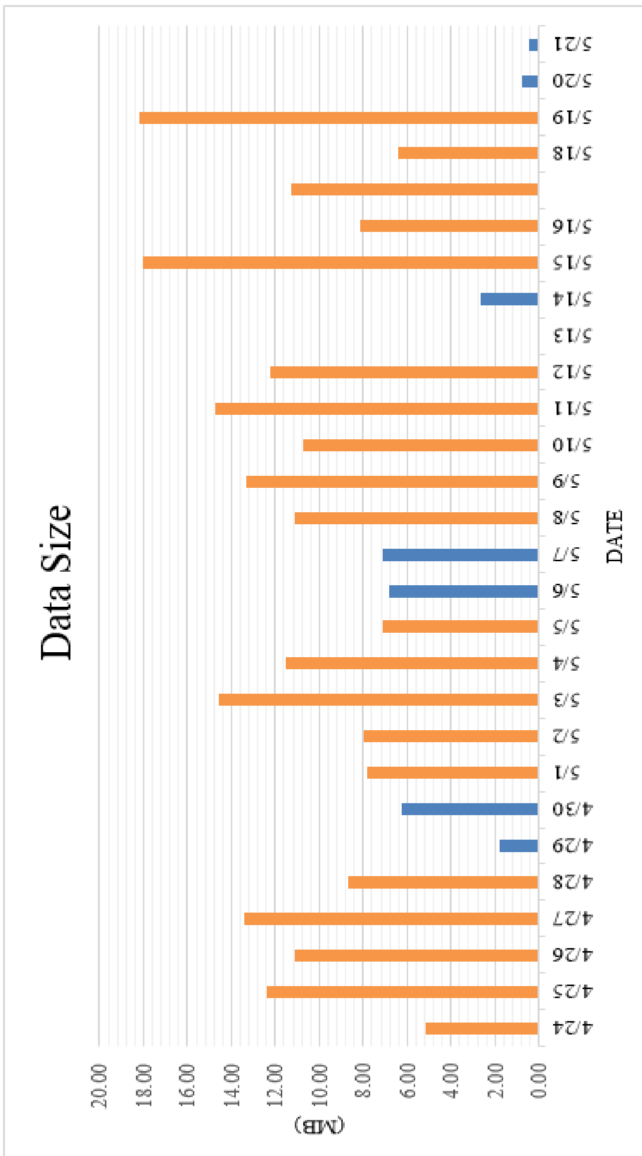


Figure F-1 Size of the collected data

Appendix G Average IC Calculation

The calculation of the ICs in the sensitivity analysis of the occupied and unoccupied hours' setpoint is shown in Table G-1.

Table G-1 Average IC in the sensitivity analysis of occupied and unoccupied hours' setpoints

Case No.		Occupied setpoint (^{0}C)	Unoccupied setpoint (^{0}C)	Energy consumption (kWh)	Base case (OCC)		Base case (UNOCC)		
					24 ^{0}C	26 ^{0}C	24 ^{0}C	26 ^{0}C	28 ^{0}C
5	a	24	24	402.18					
	b	24	26	319.51			-2.47		
	c	24	28	317.89			-1.26	-0.07	
	d	24	30	317.87			-0.84	-0.03	0.00
	e	26	26	318.02	-0.06				
	f	26	28	315.91	-0.07			-0.09	
	g	26	30	315.89	-0.07			-0.04	0.00
	h	28	28	314.82	-0.06	-0.04			
	i	28	30	314.1	-0.07	-0.07			-0.03
	Average				-0.07	-0.06	-1.52	-0.06	-0.01
7	a	24	24	351.91					
	b	24	26	298.02			-1.84		
	c	24	28	296.64			-0.94	-0.06	
	d	24	30	296.64			-0.63	-0.03	0.00
	e	26	26	296.39	-0.07				
	f	26	28	294.31	-0.09			-0.09	
	g	26	30	294.31	-0.09			-0.05	0.00
	h	28	28	293.83	-0.06	-0.02			
	i	28	30	293.42	-0.07	-0.04			-0.02
	Average				-0.08	-0.03	-1.14	-0.06	-0.01
9	a	24	24	656.25					
	b	24	26	565.49			-1.66		
	c	24	28	470.78			-1.70	-2.18	
	d	24	30	391.47			-1.61	-2.00	-2.36
	e	26	26	549.75	-0.33				
	f	26	28	464.09	-0.17			-2.03	
	g	26	30	385.55	-0.18			-1.94	-2.37
	h	28	28	447.98	-0.29	-0.45			

	i	28	30	376.33	-0.23	-0.31			-2.24
	Average				-0.24	-0.38	-1.66	-2.04	-2.32
11	a	24	24	562.89					
	b	24	26	495.29			-1.44		
	c	24	28	430.27			-1.41	-1.71	
	d	24	30	364.04			-1.41	-1.72	-2.15
	e	26	26	477.64	-0.43				
	f	26	28	419.45	-0.30			-1.58	
	g	26	30	359.63	-0.15			-1.61	-2.00
	h	28	28	402.74	-0.38	-0.52			
	i	28	30	347.62	-0.27	-0.43			-1.92
	Average				-0.31	-0.48	-1.42	-1.65	-2.02
17	a	24	24	1005.28					
	b	24	26	816.75			-2.25		
	c	24	28	635.13			-2.21	-2.89	
	d	24	30	597.22			-1.62	-1.75	-0.84
	e	26	26	806.89	-0.14				
	f	26	28	631.13	-0.08			-2.83	
	g	26	30	592.8	-0.09			-1.72	-0.85
	h	28	28	619.58	-0.15	-0.24			
	i	28	30	582.29	-0.15	-0.23			-0.84
	Average				-0.12	-0.23	-2.03	-2.30	-0.84
19	a	24	24	867.9					
	b	24	26	734.67			-1.84		
	c	24	28	598.73			-1.86	-2.41	
	d	24	30	568.63			-1.38	-1.47	-0.70
	e	26	26	720.85	-0.23				
	f	26	28	593.35	-0.11			-2.30	
	g	26	30	563.99	-0.10			-1.41	-0.69
	h	28	28	581.15	-0.18	-0.27			
	i	28	30	551.68	-0.18	-0.28			-0.71
	Average				-0.16	-0.28	-1.69	-1.90	-0.70
21	a	24	24	1325.51					
	b	24	26	1151.18			-1.58		
	c	24	28	962.74			-1.64	-2.13	
	d	24	30	794.16			-1.60	-2.02	-2.45
	e	26	26	1128.25	-0.24				
	f	26	28	950.15	-0.16			-2.05	

	g	26	30	788.28	-0.09			-1.96	-2.39
	h	28	28	925.01	-0.24	-0.34			
	i	28	30	777.1	-0.13	-0.18			-2.24
	Average				-0.17	-0.26	-1.61	-2.04	-2.36
23	a	24	24	1146.44					
	b	24	26	1016.68			-1.36		
	c	24	28	880			-1.39	-1.75	
	d	24	30	738.32			-1.42	-1.78	-2.25
	e	26	26	992.83	-0.28				
	f	26	28	864.32	-0.21			-1.68	
	g	26	30	731.49	-0.11			-1.71	-2.15
	h	28	28	837.26	-0.29	-0.41			
	i	28	30	717.32	-0.17	-0.25			-2.01
	Average				-0.21	-0.33	-1.39	-1.73	-2.14
29	a	24	24	927.46					
	b	24	26	692.62			-3.04		
	c	24	28	581.04			-2.24	-2.09	
	d	24	30	492.61			-1.88	-1.88	-2.13
	e	26	26	648.23	-0.77				
	f	26	28	523.86	-1.18			-2.49	
	g	26	30	440.55	-1.27			-2.08	-2.23
	h	28	28	452.39	-1.33	-1.77			
	i	28	30	375.81	-1.42	-1.91			-2.37
	Average				-1.19	-1.84	-2.39	-2.14	-2.24
31	a	24	24	877.52					
	b	24	26	654.26			-3.05		
	c	24	28	555.98			-2.20	-1.95	
	d	24	30	468.29			-1.87	-1.85	-2.21
	e	26	26	563.26	-1.67				
	f	26	28	460.94	-2.05			-2.36	
	g	26	30	398	-1.80			-1.91	-1.91
	h	28	28	421.08	-1.46	-1.12			
	i	28	30	349.05	-1.53	-1.60			-2.39
	Average				-1.70	-1.36	-2.37	-2.02	-2.17
33	a	24	24	1312.75					
	b	24	26	1080.4			-2.12		
	c	24	28	880.41			-1.98	-2.41	
	d	24	30	747.01			-1.72	-2.01	-2.12

	e	26	26	1087.17	0.08				
	f	26	28	857.81	-0.31			-2.74	
	g	26	30	732.91	-0.23			-2.12	-2.04
	h	28	28	830.13	-0.34	-0.42			
	i	28	30	690.8	-0.45	-0.75			-2.35
	Average				-0.25	-0.58	-1.94	-2.32	-2.17
35	a	24	24	1265.87					
	b	24	26	1037.79			-2.16		
	c	24	28	860.83			-1.92	-2.22	
	d	24	30	720.55			-1.72	-1.99	-2.28
	e	26	26	1045	0.08				
	f	26	28	822.56	-0.53			-2.77	
	g	26	30	706.61	-0.23			-2.10	-1.97
	h	28	28	781.23	-0.55	-0.65			
	i	28	30	640.03	-0.67	-1.22			-2.53
	Average				-0.38	-0.94	-1.94	-2.27	-2.26