Performance Evaluation of Mobility-Based Energy-Saving to Control Air-conditioning and Lighting Equipments

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***Abstract*—In this paper, we have developed a system that simultaneously and comprehensively simulates movement of people, motion sensing infrastructure, and air/light control facilities in indoor space like office buildings. This system has been designed to configure, validate and evaluate "task-ambient control systems" that precisely control air and light based on the detected people location and movement information (*i.e.* in a human-centric way). The proposed system has been developed based on our pedestrian simulator called HumanS that can simulate location-based systems (LBSs) involving people crowd in urban areas. In particular, we have developed (i) realistic electricity consumption model and (ii) automatic mobility generation function as new features to enable simulations of human-centric air/light control systems. Using this system with real world mobility and thermos data, we have simulated with different scenarios the performance of task-ambient control system and have revealed the dominant factors that affect the performance. We have also quantified electricity-saving effect.**

***Keywords*-human mobility and sensing, simulation, electricity-saving**

I. INTRODUCTION

After the accident in Fukushima, almost all of the nuclear plants have stopped their operation in Japan since they could not pass the safety validation tests that should guarantee survivability of the facilities. Due to this power-outage, in summer of 2011, office workers, building administrators and citizens had to be so much effortful to city-wide energy-saving. For example, under "Tokyo Energy-Saving Program" led by Environment Bureau in Tokyo metropolitan government, business offices in Tokyo were trying hard to save electricity. In particular, peak-shaving and planned outage had substantial impact on electricity-saving, which resulted in 18% cut of demand peak. According to the result of the questionnaire survey that was carried out after the program, many citizens have felt that manual control has a certain limit because we have to make a special effort to keep appropriate temperature and illuminant level, and exclude wasteful operation (like cooling air in empty rooms), satisfying certain conformance. However, electricity consumption in the commercial sector (including commercial facilities like buildings, halls and malls) occupies 19.5% of that in the entire sections [1], and thus energy-saving in those places is urgent priority.

To facilitate electricity-saving in indoor space, automated air/light control systems have recently appeared. Those systems, often called task-ambient air-conditioning and lightning, embed environmental sensors, human detection cameras and position detection sensors in buildings (e.g. office and conference rooms) , and adaptively control air and light based on the measured temperature and presence of people [2], [3], [4]. It has been reported such presence- and sensing-based task-ambient control substantially reduces wasteful power consumption [4], [5], [6], [7]. However, in the above cases, the experiments have been conducted under fully-controlled or well-equipped BEMS (Building Energy Management Systems) by the developers of those BEMS. Therefore, reports are very dependent on particular systems, facilities and settings. Meanwhile, administrators and owners of existing buildings would like to know how much benefit is expected (investment effect) if they introduce such services. Additionally, designers and developers would like to determine the optimal number and types of sensors and their locations to capture location and presence information, in order to minimize investment and maximize the electricity-saving effect. More generally, demonstrating the electricity-saving effect quantitatively must encourage those people who are planning to save energy in different ways, and have a certain impact on whole societies.

In this paper, we develop a system that simultaneously and comprehensively simulates (i) people activity, (ii) motion sensing facilities and (iii) air/light control facilities in given 2D floor maps, in order to configure, validate and evaluate task-ambient control systems. We consider the above factors ((i)-(iii)) are dominant in performance of task-ambient control systems and focus on revealing their effect. The proposed system has been developed by the HumanS simulator [8], which has been designed to simulate location-based systems (LBSs) that involve people crowd in urban areas. The main feature of HumanS is the capability of scenario creation and simulation of pedestrian agent flows as well as location detection sensors to evaluate the performance of LBSs like smart crowed navigation and sensing-based urban planning. Firstly, we have modeled realistic electricity consumption [9] by task and ambient air-conditioning/lighting facilities and other thermal sources. Based on the region–based thermal calculation model, lost and generated thermos in each region can be calculated considering all thermal sources (like human, office facilities and building thermal efficiency). All the simulated data (sensor readings, people locations, thermal information etc.) can be stored to an SQL database in a unified format so that developers can easily access the simulation results. Secondly, pedestrians' movement can be created based on the statistical data observed

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in the real world. This is a very important feature to synthesize realistic behavior since in most cases real world data is given as statistical ones. For example, the seating ratios of office workers in common offices in weekdays are given in [10], and we have used this in our case study.

We have used this system to simulate task-ambient system performance and benefit in different scenarios where sensor types, locations and unit region of air/light control are different. Using our system, we have shown electricity-saving depends on the number and location of people, sensor capability and their locations.

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II. Related Work

Adjustment of building indoor environment to building users' requirements in terms of illuminance, temperature, humidity and air-quality is one of the primary services. Such adjustment is performed by Lighting and HVAC (Heating, Ventilating and Air-Conditioning) systems, but their operations are usually coarse-grained. For example, some lighting and HVAC systems only consider two operational states (ON and OFF) applied to the entire space. Therefore, they do not consider the number of service users, resulting in huge energy loss when only a small number of occupants use a large space. By accounting the users, service provision can be more efficient, *e.g.* by stopping services for areas without users.

Task/ambient lighting systems employ this concept where more fine-grained state control is taken into account. Office space is classified into two types of areas, *task area* as the space of office users' surroundings and *ambient area* as the remaining area. In ambient area, the designed illumination intensity on desks during ON state is less (e.g. 400 lx) than the normal condition (e.g. 700 lx). Task light is operated by users in task area to provide sufficient illumination intensity for work. Task/ambient HVAC systems control air temperature in the same manner. A number of projects on these task/ambient systems have demonstrated the efficacy of such control in Japan [3], [4], [5], [6], [7] where equipments are controlled according to human presence and consequently energy consumption can be reduced by 10 up to 20 percent.

Obviously, the results strongly depend on human behavior, building architecture sensing facilities and equipment control policy. Therefore, it is desirable to reveal how these factors affect each other and how they dominantly affect the energy consumption. Yamaguchi [9] and Page [11] have modeled human behavior using a Markov chain in order to represent realistic human behavior and evaluate its effect on the energy consumption. However, they employ roughly-classified state models and do not consider realistic mobility of building users.

On the contrary, our system proposed in this paper is intended to evaluate the service effect on building energy saving, based on detailed, realistic modeling of human behavior, sensing facilities and control policy. To our best knowledge, this has not been considered so far in past literature.

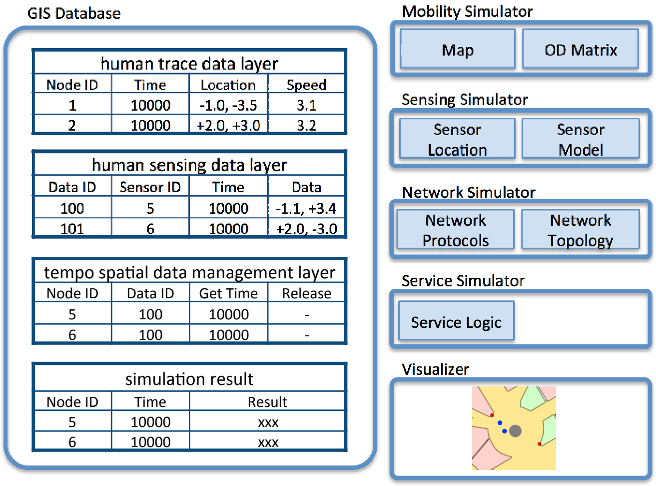
III. System Design

In this paper, we design and develop an environment (*i.e.* a toolset) to design, validate and evaluate electricity-saving systems that control lighting and air-conditioning equipment based on people location and movement. These systems obtain people locations from infrastructure (like embedded sensors), analyze them and control the equipment to keep appropriate temperature and illuminance levels. Using our toolset, we can simulate (i) human location and movement, (ii) sensor behaviors and (iii) air-conditioning/lightning control facilities so that we can observe the effect and benefit by such facilities, dependency between different factors such as location sensing resolution/capability and control policies.

This toolset is capable of simulating indoor people mobility, sensing behavior and control facility. This simulation engine is designed based on our human mobility sensing simulator called *HumanS* [8] that models realistic behavior of pedestrians. HumanS works with a geographic information system (GIS) and integrates a GIS database to manage location-dependent data generated in simulation processes. Utilizing the HumanS simulator as the simulation core, our simulation is conducted in the following way. Firstly, indoor people mobility simulation is performed where the trace data of human agents (ground truth) are stored as a dataset at "human trace data layer" in the GIS database as shown in Fig. 1. Then mobility sensing simulation is performed where these trace data (ground truth) are read from "human trace data layer", and accordingly location sensing results are generated and stored as a dataset at "human sensing data layer". The location sensing results may differ depending on sensor types and capabilities. For example, laser-range scanners can detect the presence of people in wide angle and range (*e.g.* 270° and 30m, respectively) except those behind other people (due to scan blocking). WiFi-based location sensing can detect only people with WiFi mobile devices but there is no blind zone in the wireless range. Finally, the control facility to be examined should be implemented in the control simulator part as a set of decision rules to determine turn-on/off or air conditioner and light operations, based on the location sensing dataset in "human sensing data layer". For example, the simplest rule based on location sensing is to turn on the light if at least one person is detected in a certain area, and to turn off if no people is detected for a while. We may choose an appropriate electricity consumption model for each equipment we use in the simulation.

A. Indoor Mobility Simulation

Realistic indoor mobility simulation is important since it becomes "ground truth" of people location for the subsequent location sensing simulations. In indoor mobility simulation, we specify the set of logical locations (like office rooms, meeting spaces) in the area and the people density (population) for each location. Sometimes real people location data is provided by people traces, but



human trace data layer

Node ID	Time	Location	Speed
1	10000	-1.0, -3.5	3.1
2	10000	+2.0, +3.0	3.2

human sensing data layer

Data ID	Sensor ID	Time	Data
100	5	10000	-1.1, +3.4
101	6	10000	+2.0, -3.0

tempo spatial data management layer

Node ID	Data ID	Get Time	Release
5	100	10000	-
6	100	10000	-

simulation result

Node ID	Time	Result
5	10000	xxx
6	10000	xxx

Figure 1. Architecture of HumanS

due to difficulty of tracking people in indoor space, it is provided by people density in most cases. Based on the given density at different locations in the map, transit probabilities between locations can be determined. The problem to derive such probabilities can be formulated as the optimization problem that minimizes the difference between the derived and the observed population at each location. Based on the derived probabilities, our simulator can determine the whole-day mobility of human agents (pedestrian agents) that move around different locations satisfying the given population data in average. Some part of this function relies on our HumanS simulator but due to space limitations, we omit mobility generation details in this paper, and we would like to focus more on control system modeling and thermos modeling, which are explained in the following sections.

B. *Sensing Simulation*

In the location sensing simulation, detecting people locations by installed sensors is simulated. At first, the sensors are located on the map according to a given simulation scenario. These sensors can detect the presence of nodes only when the nodes are in their scan ranges. Given human trace data (ground truth) that have already been generated in the GIS database (by indoor mobility simulation) and sensor capabilities such as scan ranges and detection ratios, the location sensing simulator calculates the nodes that are supposed to be detected by these sensors, and stores the results to the human sensing data layer. We note that scan ranges are defined based on the specification of sensors. For example, for infra-red based position sensitive detectors, lines are used to represent scan range where pedestrians who cross the lines are detected. Laser-range scanners can detect nodes in fan-shaped scan regions by laser light and can continuously measure nodes' locations. These sensing data (detected/measured human traces) are stored into the human sensing data layer.

C. *Air/Light Control Facility Simulation*

The control facility simulation part simulates the operation of air-conditioning and lighting equipments based on given rules and the sensing data generated by the sensing simulation. In addition, it estimates energy consumption for heating, cooling, ventilation and lighting for the studied office area.

We explain briefly how we estimate energy consumption of air-conditioning and lighting. Heating, cooling and ventilation are provided for each service area. A certain amount of fresh air must be introduced to the conditioned service area. The minimum amount can be defined to be $25m^3$ per person. The rated volume of ventilation was assumed to be $5m^3$ per hour that is equivalent to $25m^3$ per person with 0.2 persons per m^2 of floor space. The occupants density was assumed according to the survey on actual office buildings done by Ishino et al. [12]. The ventilated air is released to the conditioned space after exchanging heat with air ejected from service area in order to reduce ventilation heat load. The heat exchange efficiency was assumed to be 60%. In this paper, we assumed that the office space is equipped with multi-split type air conditioners consisting of a number of indoor units and an outdoor unit. Indoor units exchange heat between indoor air and refrigerant delivered from the outdoor unit through refrigerant pipeline. Outdoor unit releases heat to outside air. The total heat exchange efficiency under the rated condition is defined by coefficient of performance, COP, indicating the ratio of inputted electricity to the system and generated heat in the outdoor unit. The rated COP was assumed to be 3.6 for cooling and 4.6 for heating. In order to model the operation of the system, first, heating and cooling requirement is estimated by using thermodynamic simulation [13] using the response factor method [14] while taking into account heat flow through building envelops and windows, ventilated air, and internal heat gain from human body, light, and other office equipment. The heating and cooling requirement is converted to the volume of air provided to the service area with a defined temperature, 14° for cooling and 34° for heating. Then, the amount of heat exchanged by the indoor unit of air-conditioning system to create the volume of air is calculated. Dehumidification is also taken into account during cooling operation. The total exchanged heat is quantified by summing up the exchanged heat of all the indoor units connected to the outside unit. Finally, energy consumption by the outside unit for heating and cooling is determined by using a regression model modeling the relationship among the heat load for heating and cooling, ambient air conditions, and energy input. Energy consumption for lighting is determined by the operation condition defined the sensing simulation and the rated electricity input to lighting device. The detail of the model is given in Refs [13], [15].

IV. SIMULATION STUDY OF ENERGY-SAVING IN OFFICE BUILDING

We have evaluated several control facilities for air-conditioning and lighting with different office workers behavior models in an office building using the proposed simulation environment. In order to evaluate energy consumption reduction by the facilities while keeping thermal and luminous comfort, we have examined both energy consumption and service availability in the simulations. In particular, we have measured the amount of

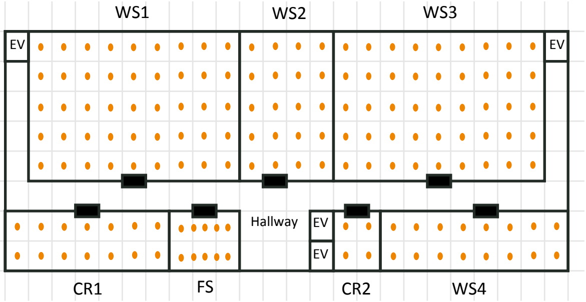


Figure 2. Floor Plan Used in Simulation Experiments

electricity consumed by the air-conditioning and lighting systems. The *energy consumption ratio* is defined to mean the ratio of energy reduction by a control facility to the entire consumption. The *service availability* is defined as duration during which workers can take services with adequate levels from air-conditioning and lighting systems in their offices. The simulations were conducted using the $40m \times 120m$ floor plan shown in Fig. 2. We assumed there were 126 workers on the floor.

A. Mobility Model

We have modeled the mobility of workers on the floor based on the proposed behavior model shown in Section III-A, according to the following policies. These workers take at each moment one of the following actions, working at their offices, going out of the floor, having a meeting with colleagues and having a break. Each worker belongs to one of four offices (WS1, WS2, WS3 and WS4) and never goes to the other offices. This behavior can be modeled as the state transition diagram shown in Fig. 3. Each circle (state) represents each behavior in the figure. When she/he works at her/his office, she/he selects one of the desks in his office and works at the desk for a while. This behavior is represented as P_1 in Fig. 3. The desks are represented as small circles in Fig. 2. There are 45, 20, 45 and 16 desks in WS1, WS2, WS3 and WS4, respectively. When she/he leaves the floor, she/he goes to one of the four elevators (EV) and disappears. When she/he has a meeting, she/he goes to one of the meeting rooms (CR1 and CR2). These meeting rooms have different space sizes. CR1 and CR2 have 14 and 4 seats, respectively. When she/he has a break, she/he goes to a rest station (FS) and rests for a while. Q represents a probability that a worker in a state changes her/his behavior to take another behavior specified in another state. The probabilities between two states determine how many workers move from one place to another place. In order to realize realistic situations on the floor, we gave the number of workers in each place according to the statistics data shown in Ref. [12]. Ref. [12] investigates the number of workers who stay on a real floor every 10 minutes in weekdays. We derive the state transition probabilities that can realize the number of workers for each place every 10 minutes. Fig. 4 shows the population of the four offices in a day. The red lines in Fig. 4 represent real data in Ref. [12]. The black lines represent the number of workers derived by our proposed method. We can see that our method can realize similar situations and can represent the realistic situation in the building.

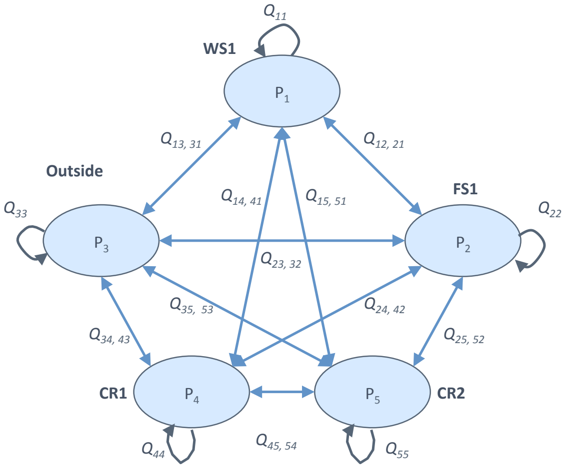


Figure 3. Behavior Model of Workers in WS1

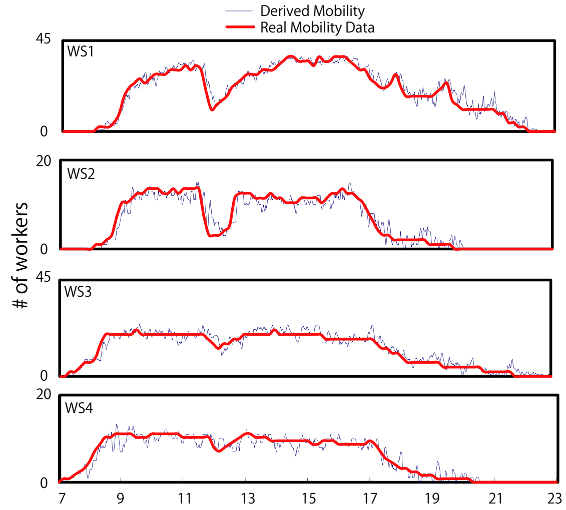


Figure 4. Number of Workers in WS1, WS2, WS3 and WS4

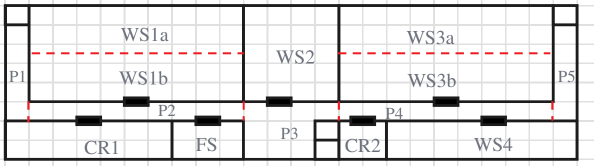


Figure 5. Dividing Offices (Large)

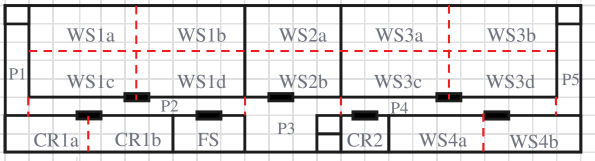


Figure 6. Dividing Offices (Small)

Workers in state P_1 select their desks to work. We examined two "desk selection" strategies of the workers in this study. In the "selection strategy without priorities" (random-based selection policy), workers select their desks randomly, while in the "selection strategy with priorities" (priority-based selection policy) they select desks according to priorities defined for the desks. We divided the offices into several areas as shown in Figs. 5 and 6, and allocated the same priority to the desks in the same region. Since the desks with the same priority are located close to each other in the offices, workers are also likely to close to each other in the priority-based selection policy. Therefore, we can expect to reduce the total amount of energy consumption by turning off the equipment serving regions with few workers. We also examined two different priority allocations for desks. There are two priorities in WS1 and WS3 and no priority in WS2, WS4, CR1 and CR2 in the allocation shown in Fig. 5. WS1a has higher priorities than WS1b in WS1. In the same way, WS3a has a higher priority than WS3b in WS3. The other allocations are shown in Fig. 6. There are four priorities in WS1 and WS3, two priorities in WS2, WS4 and CR1 and no priority in CR2. We will see how these allocations affect the total amount of energy consumptions through experiments.

B. Control Facilities

We prepare an ambient air-conditioning equipment and a combination of task and ambient lighting systems for simulation experiments. The ambient air-conditioning systems are installed in the offices. Their “set point temperature” (goal state) was assumed to be 26° for cooling and 22° for heating. An ambient lighting equipment brightens large area in the office. On the other hand, each desk has its task lighting equipment to provide lighting for each worker. Both task and ambient lighting systems are operated together to provide necessary and sufficient lighting for workers to reduce the total amount of energy consumption. Basically, the air-conditioning and lighting systems are tuned on if there are some people in their service areas, and tuned off otherwise. In order to evaluate how the service area affects the system performance, we apply different service areas to the ambient air-conditioning and lighting systems.

We applied two room division strategies to both ambient systems as shown in Fig. 5 and Fig. 6. WS1 is divided into two regions WS1a and WS1b in Fig. 5. It means that there are two ambient air-conditioning facilities and lighting facilities in WS1. On the other hand, there are four ambient air-conditioning facilities and lighting facilities in WS1 since WS1 is divided into four regions WS1a, WS1b, WS1c and WS1d.

We also use three types of sensors so that we can evaluate how the capability of sensors affects the energy reduction effect. We examine “perfect sensors” as a benchmark that can detect all workers without errors to measure the ideal performance. We also examine infrared sensors and camera sensors. These sensors are placed in the office as shown in Figs. 7 and 8. In those figures, sensing regions and workers are represented as orange regions and blue circles, respectively. Workers in orange regions can be detected by sensors. Fig 7 shows the allocation with infrared sensors. The infrared sensors can detect workers that stay in $1m$ circle region from the sensor. We place many camera sensors in another allocation shown in Fig. 8. The sensing region of camera sensors can be represented as fan-shaped orange region.

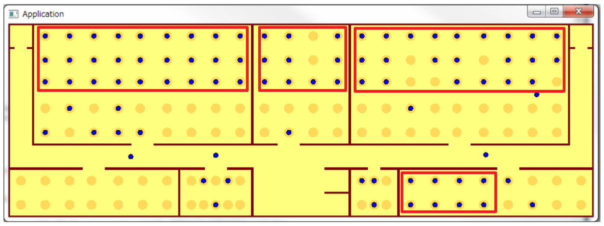


Figure 7. Infrared Sensors

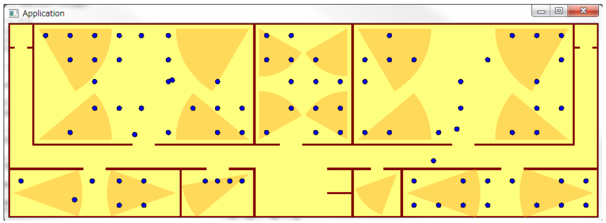


Figure 8. Camera Sensors

We will see how these differences affect the system performance through simulation experiments.

C. Simulation Results

We have conducted simulations with nine simulation scenarios that are differentiated by worker behavior, control facilities or service areas, as shown in Table. I. The energy consumption ratio of air-conditioning and lighting and the service availability of air-conditioning and lighting are shown in Fig. 9 and Fig. 10, respectively. Scenario (a) is a benchmark scenario that keeps all systems on all the time. In this case, the energy consumption by lighting was 40.9 $kWh/year \cdot m^2$, which is calculated by the control facility simulation. Similarly, the energy consumption by air-conditioning was 49.3 $kWh/year \cdot m^2$ since 294.2 $MJ/m^3 \cdot year$ and 123.8 $MJ/m^3 \cdot year$ are required for heating and cooling, respectively. These results are the baselines, and we can see that the energy consumption ratios are 0% and the percentage of the service availability is 100 % in the figures. The other scenarios, which control systems based on the sensing data, could reduce up to 37% of energy consumption by air-conditioning and up to 58 % of energy consumption by lighting. The percentage of the service availability varies depending on the scenarios.

Table I
SIMULATION SCENARIOS

	Behavior	Control Facility	
	Desk Selection	Sensor	Service Area
(a)	without priorities	N/A	Large
(b)	without priorities	Infrared Sensor	Large
(c)	without priorities	Camera Sensor	Large
(d)	without priorities	Perfect Sensor	Large
(e)	without priorities	Infrared Sensor	Small
(f)	without priorities	Camera Sensor	Small
(g)	without priorities	Perfect Sensor	Small
(h)	with priorities	Perfect Sensor	Large
(i)	with priorities	Perfect Sensor	Small

By comparing scenarios (b) and (d) that use the same settings except sensors, we can see that the control facility with the infrared sensors could achieve high energy consumption like with perfect sensors. Also, we can see the same trend in small service areas by comparing scenarios (e) and (g). From these results, although the sensing range of infrared sensors is small, infrared sensors

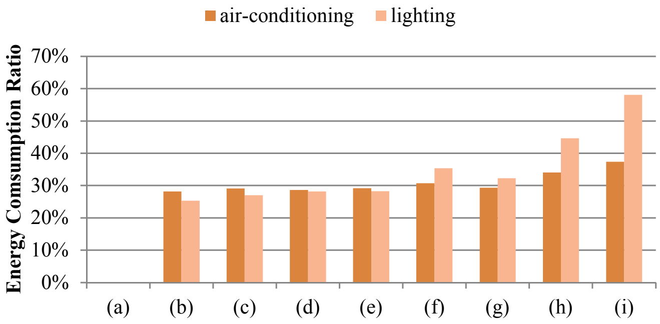


Figure 9. Energy Consumption Ratio of Air-conditioning and Lighting

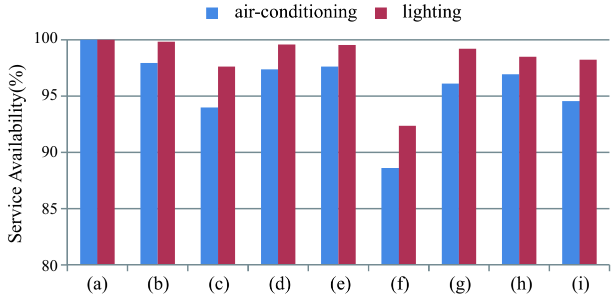


Figure 10. Service Availability of Air-conditioning and Lighting

could detect workers with high accuracy and contribute to reduce energy consumption. Similarly, the control facility with camera sensors could reduce same energy consumption as shown in scenarios (c) and (f). However, service availability in the scenarios is low because the control facility kept the equipment off even if there were some workers. This is because camera sensors did not cover all the area in the offices and could not perfectly capture all the workers. Thus, we can know that more camera sensors are needed to keep service availability high.

In order to evaluate how workers behavior affects the system performance, we compared scenarios (d) and (h) that have different behavior models. We can see that both control facilities keep service availability high. However, the energy consumption ratios of air-conditioning are 28.7 % and 34.1 %, and those of lighting are 28.2 % and 44.7 %, respectively. The priority-based seat selection can contribute to energy reduction keeping service availability. We can see the same trend in scenarios (g) and (i). According to scenario (i), the energy consumption ratios of air-conditioning and lighting are 37.4% and 58.1%, respectively. This indicates that smaller service areas also contribute more to reduce energy consumption ratio because the equipments can be controlled more precisely.

V. Conclusion

We have developed a system that simultaneously and comprehensively simulates people activity, location sensing facilities and air/light control facilities based on location information. This has aimed at provisioning a fruitful toolset that allows designers to configure, validate and evaluate task-ambient control systems in energy management systems. The proposed system has been developed by the HumanS simulator [8], but we have added several features like realistic electricity consumption models and automatic generation of pedestrians' movement based on the statistical population data.

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