Evaluation of energy-saving performance of office building task/ambient systems considering dynamic worker's behaviour

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ABSTRACT

The authors developed a model that simulates task/ambient lighting and air-conditioning systems for office building. In the model, first, the stochastic mobility of office workers is simulated as the Markov Chain process. Then, the movement of the sensors used in the task/ambient systems to detect the location/movement of office workers is simulated. Then, the sensors' information is converted to the operation of office equipment, lighting devices, air-conditioning and ventilation systems, and finally energy consumption is quantified. Thus, the whole model is capable of simulating heat and electricity demand of office buildings while taking into account the human mobility and the configuration and the operation strategy of sensor systems in addition to elements usually considered in the building performance simulation, such as geometry and insulation performance of the building. By using this model, the authors evaluated two types of sensor systems "infrared sensors" and "camera sensors" with different capability while assuming an office floor equipping task/ambient lighting and air-conditioning systems.

KEYWORDS

Office building, Human mobility simulation, sensor

INTRODUCTION

Energy management has become one of the most important issues in Japan after the explosion of the Fukushima nuclear power plants due to the shortage of the electricity supply capacity. For reducing electricity consumption of office buildings, task/ambient control of lighting and air-conditioning systems would be effective. However, software has not been well established to simulate task/ambient systems. In the simulation of task/ambient systems, 1) behaviour model of office workers, 2) movement of sensors to detect presence or movement of office workers, and 3)

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building equipment (lighting and air-conditioning system) must be integrated. This paper presents a simulation model integrating these three components to simulates the performance of task/ambient systems for office application.

The simulation of 1) and 2) is performed by a model called "Humans" developed by the Kanaya et al. (2012). The simulation 3) is performed by an energy demand model developed by Yamaguchi et al. (2008). The second section introduces the simulation models and the integration of the models. Then, an application of the integrated model to a hypothetical office floor is presented. In the application, we evaluated the performance of task/ambient lighting and air-conditioning systems while assuming two kinds of configuration of sensors using "infrared sensors" and "camera sensors" with different sensing capability. Energy conservation effect by the task/ambient systems and error made by the sensors were evaluated.

SIMULATION MODEL

Figure 1 shows the simulation procedure of the integrated model. As mentioned earlier, the model can be divided into three components.

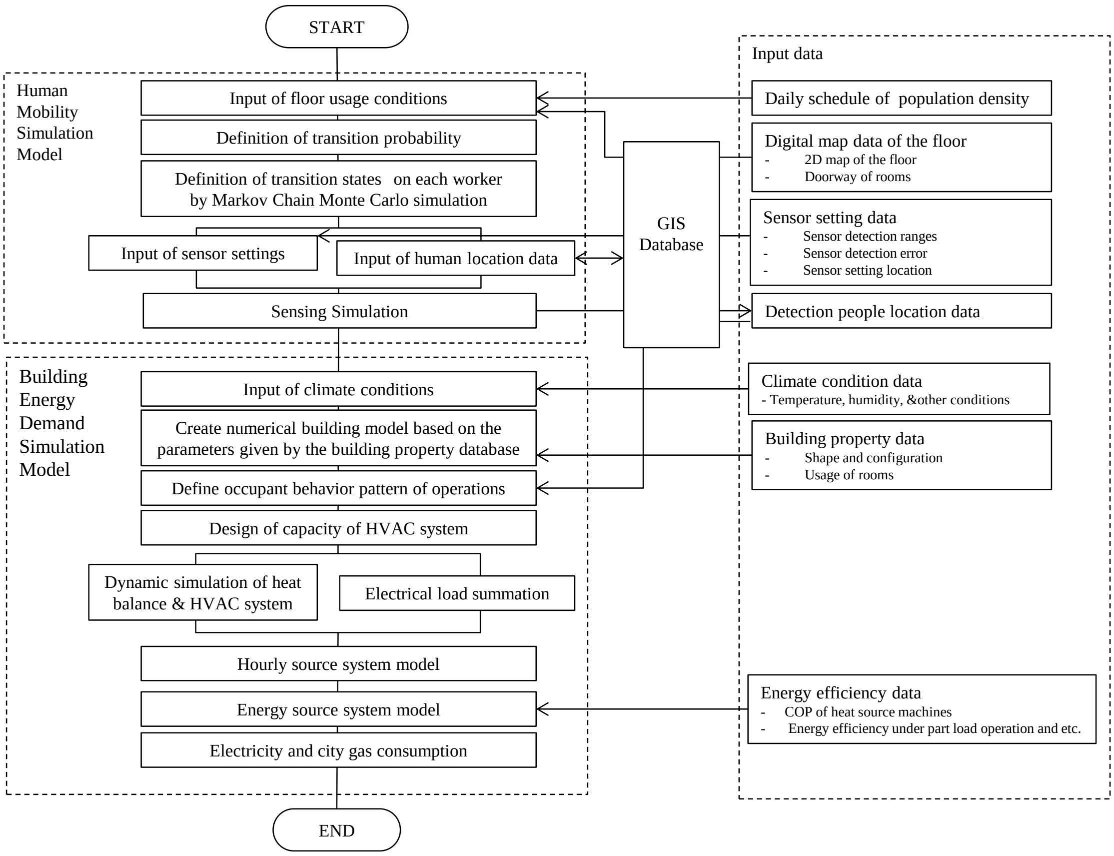

Figure 1. Overall flowchart of simulation model

The first component is the simulation of movement and location of office workers done by the Humans with 10-min time resolution. In the simulation, the behaviour of each office worker is modelled as Markov Chain process assuming five transition states, as shown in Figure 2. There are five transition states of workers represented by S1 to S5. The transition probabilities from transition state i (S1 to S5) to *j* (S1 to S5) are shown by P_{ij} in the figure. The method to quantify P_{ij} is explained in the next section.

HumanS integrates a GIS database of the floor to manage location-dependent data generated in simulation processes. We set a desk with specific location on the floor at which each worker works while the worker is in the state S1 (working at a desk). Similarly, the location of workers is decided based on the transition states. When a worker transfers between two transition states, the corresponding route through which the worker moves is defined on the floor so that we can simulate realistic transition mobility while avoiding obstacles and other workers. The simulated human mobility data stored in GIS database is used in the simulation part of sensors.

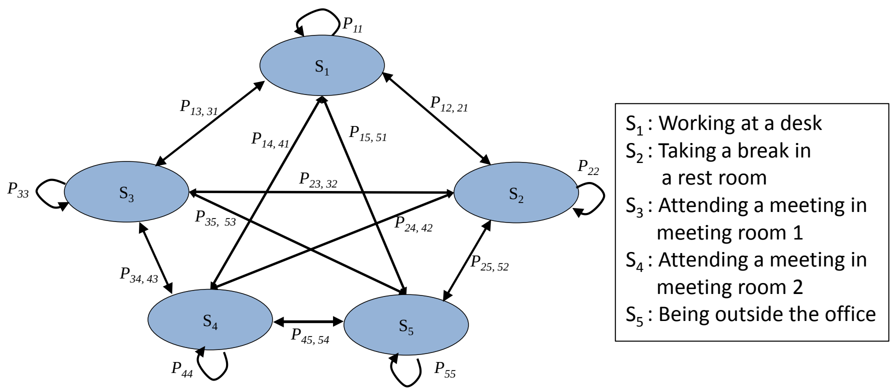

Figure 2. workers behaviour transition

Second, the operation of sensors is simulated. The location and movement of office workers are generated by the Humans. The information is converted by the sensor simulation to the operation of lighting devise and air-conditioning systems. Before the simulation, the location at which the sensors are installed and the range and monitoring frequency of the sensors to detect the presence of office workers are defined. We defined the following three types of sensors with different sensing capability in order to evaluate how the sensing capability affects the energy performance and sensing error:

- Perfect sensor that can detect all workers without errors to assume the ideal performance,
- Infrared sensor that detects workers that stay in 1 m circle region from the sensor, and
- Camera sensor that has a fan-shaped horizontal sensing region with a length and a central angle.

We assumed that the air-conditioning system and ambient lighting are to be ON while there is at least one person is detected by the sensors in the room. In case that task/ambient lighting system is adopted, we assumed that task lights are to be ON while the worker who uses the desk is detected by the sensor at the desk. The space heat and cooling load is dynamically calculated using the weighting factor method (ASHRAE 2001) developed for HASP/ACLD (Matsuo 1985a) which is the computer program by Japanese researchers during the 1970s and 1980s (Matsuo 1985b). For lighting, electricity consumption of each lighting device is defined and the operation condition is given by the sensors' simulation. The validation of the model is given elsewhere (Yamaguchi et al., 2010).

APPLICATION TO A HYPOTHETICAL OFFICE FLOOR

Figure 3 shows the layout of the hypothetical office floor to which the model was applied. The floor area is 4,800 m^2 and the number of office workers is 126. These workers have a desk in one of the four office rooms, WS1 to WS4. In the WS1, WS2, WS3, and WS4, there are 45, 20, 45 and 16 desks respectively. The room CR1 and CR2 in Figure 3 are used for meeting. The rest room indicated "FS" is located next to the elevator hall. When a worker works in an office, he/she selects one of the desks indicated by small circles in Figure 4.

In order to perform realistic situation, the transition probability for each transition states was assumed by using available data. First, the average number of workers was given by a data measured on an existing office building by Ishino et al. (1997). The schedule of meetings and attendees was given as shown in Table 1. Additionally, average duration of break (State S2) was available. As there are several combinations of transition probability that satisfy the data related to each transition states. Thus, we applied linear programming method to minimizes the difference between the data and simulated data.

Table 1. The schedule of meetings and attendees

Meeting room	*Time*	*Occupied by*	*Number of attendees*
CR1	10:00-10:30	WS3	6
	13:00-14:00	WS1	4
	16:00-17:00	WS3	12
CR2	9:00-10:00	WS1	4
	11:00-11:30	WS2	4
	14:00-15:00	WS4	3
	15:30-16:10	WS2	3

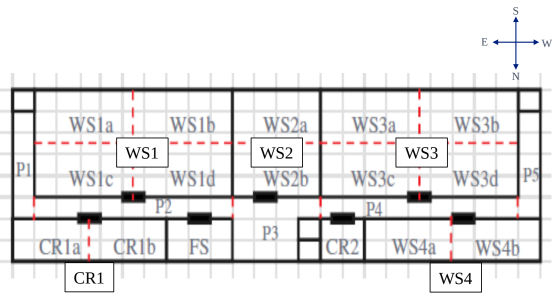

Figure 3. floor layout and dividing area

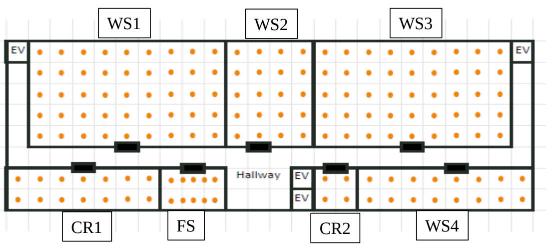

Figure 4. desk layout

For lighting, the illumination intensity was assumed to be 700 lx on desks of workers. The electricity consumption was assumed to be 12.0 W/m ^{2} without the adoption of task/ambient lighting system. With the task/ambient system, the electricity consumption of ambient lights was assumed to be 7.7 W/ m^2 while that of task light was assumed to be 4.3 W/m^2, the total electricity consumption was assumed to be the same.

For air-conditioning system, the set point temperature was assumed to be 26 degree for cooling and 22 degree for heating. The air-conditioning system is VRV HVAC system. The rated coefficient of performance (COP) of the system was assumed to be 3.0 for cooling and 4.0 for heating. The outside unit was assumed to adopt inverter control that improves COP under a part load operation. When ambient air-conditioning system is used, the rated volume of ventilation was assumed to be 25 m^3/hour per person, and the ventilation system is controlled according to the number of workers in each room. When ambient air-conditioning system is not used, the rated volume of ventilation was assumed to be 1.2 m^3/m^2 per hour, and the ventilation system is turned on if there is at least one person in the room.

Based on the result of sensors' detection of office workers, the area for which lighting and HVAC are operated was determined. The unit of operation for lighting and HVAC is shown by the red lines in Figure 3. When at least one person is detected by the sensor, lighting and HVAC systems were assumed to be operated in the area.

As mentioned earlier, the infrared sensor detects workers that stay in 1 m circle region from the sensor. We assumed that an infrared sensor is equipped on the ceiling at the desk of each worker. Figure 5 shows the sensing regions as orange regions while workers are indicated by blue circles. The infrared sensor cannot distinguish the worker staying at his/her desk and workers who walk through the sensing region.

The camera sensor has a fan-shaped horizontal sensing region with a length and a central angle. Figure 5 shows the sensing region of camera sensors. We assumed to combine three types of camera sensors with different sensing length and central angle (15 m and 45 degree, 15 m and 30 degree, and 10 m and 30 degree). The sensor cannot detect workers if the workers locate on the same radial line as others from the sensor. In addition, there are several blind angles.

Both of the sensors have dead region at which the existence of office workers cannot be detected. Such sensing error was evaluated by using an indicator, service availability, calculated as the ratio of the sum of the time during which task light and air-conditioning was provided over the sum of the time during which the office workers spent time at his/her desk.

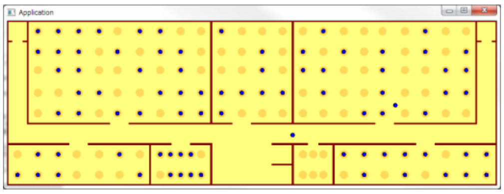

Figure 5. Iinfrared sensors

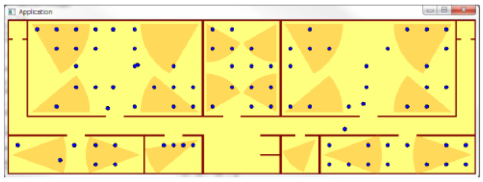

Figure 6. Camera sensors

SIMULATION CASES

Table 2 lists the simulation cases assumed in this paper. The listed five cases were made with the combinations of the desk selection of the workers, the configuration of sensors, the adoption of task/ambient systems.

We examined two desk selection strategies. With the "fixed seat policy", the workers use their desks allocated individually, while with the "minimum space use policy", the workers select desks to minimize the conditioned rooms.

Table 2. Simulation scenarios

Case	*Desk selection*	*Sensor*	*Task/ambient control system*
Case1	Fixed seat	N/A	N/A
Case2	Fixed seat	Infrared sensor	Applicable
Case3	Fixed seat	Camera sensor	Applicable
Case4	Fixed seat	Perfect sensor	Applicable
Case5	Minimum space use	Perfect sensor	Applicable

RESULTS

Figure 7 shows the number of workers in the four offices in one representative day. The red lines show the actual occupancy (Ishino et al. 1997) used as input of the Humans, while the black lines show the simulation result. The results showed a good agreement with the actual occupancy and a stochastic feature of occupant behaviour in office floors.

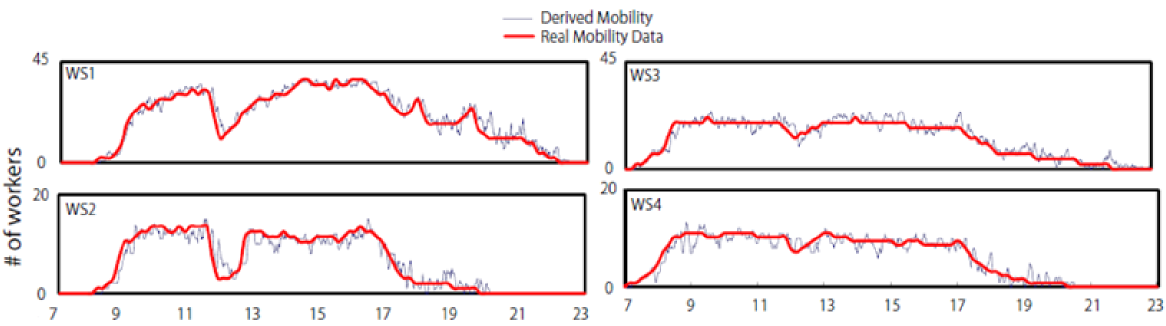

Figure 7. the population of the four offices in one day

Figure 8 shows the service availability. The service availability of Case 4 was set to be 100 % as the reference case assuming that the sensors perfectly detect the location of the workers. In Case 2, the service availability was 102% for air-conditioning while 100% for lighting. The reason of the overestimation was that the infrared sensor detect workers located in its sensing region without distinguishing the workers conditions sitting at desk or walking through the sensing region. In Case 3, the service availability was 92 % for air-conditioning and 93% for lighting. In 8 % and 7 % of time and area during which air-conditioning system and lighting must be operated, the systems were not operated. This is because the camera sensors have dead zones in the office and cannot detect the workers perfectly.

Figure 9 shows the result of energy consumption for lighting and air-conditioning.

Case 1 is the reference case in which any task/ambient system was not adopted. By comparing Case 1 and Case 4, the energy conservation effect by the task/ambient systems can be quantified. It is 34% for lighting and 12% for air-conditioning. Comparing Case 1 and Case 2, the energy demand reduction ratio is 31% of lighting and 12% of air-conditioning. From these result, although infrared sensor has small sensing ranges, but it can detect workers with high accuracy. The energy demand of Case 3 is smaller than that of Case 4, because the service availability of lighting and air-conditioning are not enough.

In order to evaluate how worker's behaviour (the desk selection strategy) affects the system performance, we compare scenarios Case 4 and Case 5. It was observed that both control facilities keep high service availability, but the energy demand in Case 5 is 15% lower than that in Case 4. This result implies that task/ambient systems minimizing the service provided according to sensing occupant behaviour would significantly reduce energy consumption for lighting and air-conditioning.

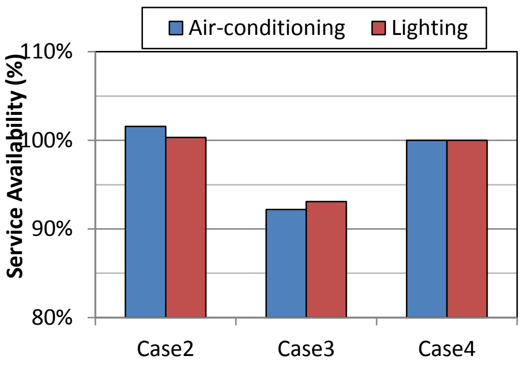

Figure 8 . Service availability

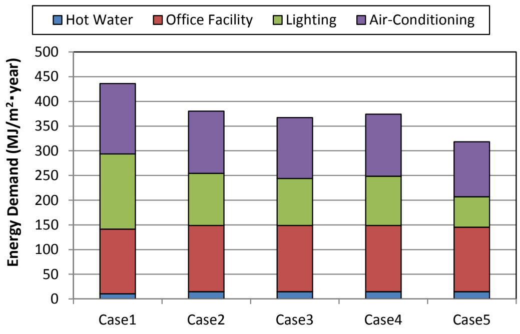

Figure 9. Energy demand

CONCLUSION AND IMPLICATIONS

We developed a simulation model that simultaneously and comprehensively simulates indoor location and movement of workers, the motion of sensing infrastructure, and the operation and energy performance of lighting and air-conditioning systems of office buildings. The result generally indicates that the model contributes to configure, validate and evaluate task/ambient control systems in terms of the energy efficiency and the quality of service provided to office workers.

Regarding the sensors capability, task/ambient systems using the infrared sensor is able to provide service to workers, while it overestimate the occupancy because it detect workers walking through the sensing region. On the contrary, task/ambient systems using the camera sensor overlooks needs of the service since the sensor have blind angles in the room. As further work, we would like to simulate that in entire office building, including not only office rooms and conference rooms but also public space (toilet, corridor, and elevators).

ACKNOWLEDGEMENTS

This study was supported by the Ministry of Education, Culture, Sports, Science and Technology, Japan. We note that this work has been done within a joint project between Graduate School of Information Science and Technology and Graduate School of Engineering, Osaka University. This paper is also supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science, No. 22360237.

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