Estimating the relationship among occupant behaviours and indoor environmental parameters using Bayesian networks

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This paper investigates the relationship among occupant behaviors and indoor environmental parameters. We collect data from three aspects: indoor environmental variables measured by a wireless sensor network, body sensors carried by occupants, and questionnaires completed by occupiers. The wireless sensor network measures four parameters: temperature, humidity, light and barometric pressure. The body sensors measure collect data including burned calories, physical activity, body position, and galvanic skin response from their wearers. The questionnaire collects data such as occupier's behaviour and mood. The experiment is conducted in an air-conditioned office where temperature can be controlled by the occupants. Based on such information, we build up a Bayesian network model revealing how indoor environmental parameters and occupant's behaviour impact physical parameters of human bodies. We also compare our models with Fanger's thermal comfort model.

1. INTRODUCTION

The increasing miniaturisation of RF devices and microelectro-mechanical systems (MEMS), as well as the advances in wireless technologies, has generated a great deal of research interest in the area of wireless sensor networks (WSNs), which provide a promising infrastructure for gathering information about parameters of the physical world.

A WSN system is a group of sensors linked by wireless medium to perform distributed sensing tasks. WSN systems have attracted a wide interest from academia and industry alike due to their diversity of applications. Recent advances in wireless sensor network technology have enabled the development of low-cost, low-power, multi-functional sensor nodes that are small in size and allow untethered communication over short distances. Such systems allow close monitoring and adaptive control of building equipment, materials performance (such as those in the façade) and environmental conditions including temperature, air flow, indoor air quality, lighting , sound and the stated well-being of the occupant in relation to their surroundings.

Systems will also enable a proper cohesive data management system to be organised for buildings which will help to understand the strategies required for operating the building so that energy and water savings are achieved; environments are healthier; and there is closer relationship between the occupant and the building. It will also help to achieve a leaner and more effective design, construction, operation and facilities management regime. For example we should be able to understand very much more deeply the patterns of use and also enable prediction of failure conditions thus informing maintenance regimes.

A Bayesian network is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data analysis. Firstly, a Bayesian network can be used to learn causal relationships, and hence can be used to gain understanding about a problem domain and to predict the consequences of intervention. Secondly, because the model has both a causal and probabilistic semantics, it is an ideal representation for combining prior knowledge (which often comes in causal form) and data. Therefore, it is worthwhile to use Bayesian networks to explore the relationship among various variables that might influence indoor air quality, occupant's productivity, and other variables of interest. Readers are referred to Jensen (2001), and Neapolitan(2003) for better understanding in the Bayesian networks.

There is now much evidence to show that the environment of buildings can affect the work performance of the occupants and can alter their state of well-being (Clements-Croome, 2005). This means that environmental design can enhance the value of the built asset for an organisation. This paper investigates the relationship among occupant behaviors and indoor environmental parameters. We collect data from three aspects: indoor environmental variables measured by a wireless sensor network, body sensors carried by occupants, and questionnaires completed by occupiers. The wireless sensor network measures four parameters: temperature, humidity, light and barometric pressure. The body sensors measure collect data including burned calories, physical activity, body position, and galvanic skin response from their wearers. The questionnaire collects data such as occupier's behaviour and mood. The experiment is conducted in an air-conditioned office where temperature can be controlled by the occupants. Based on such information, we build up a Bayesian network model revealing how indoor environmental parameters and occupant's behaviour impact physical parameters of human bodies.

2. EXPERIMENT SETTINGS

We are interested to build a sense diary that can serve two-fold purposes: to minimise energy consumption, and to maximise occupant productivity. In order to achieve these two objectives, a research plan is set as shown in Figure 1. We planed to use wireless sensors to measure

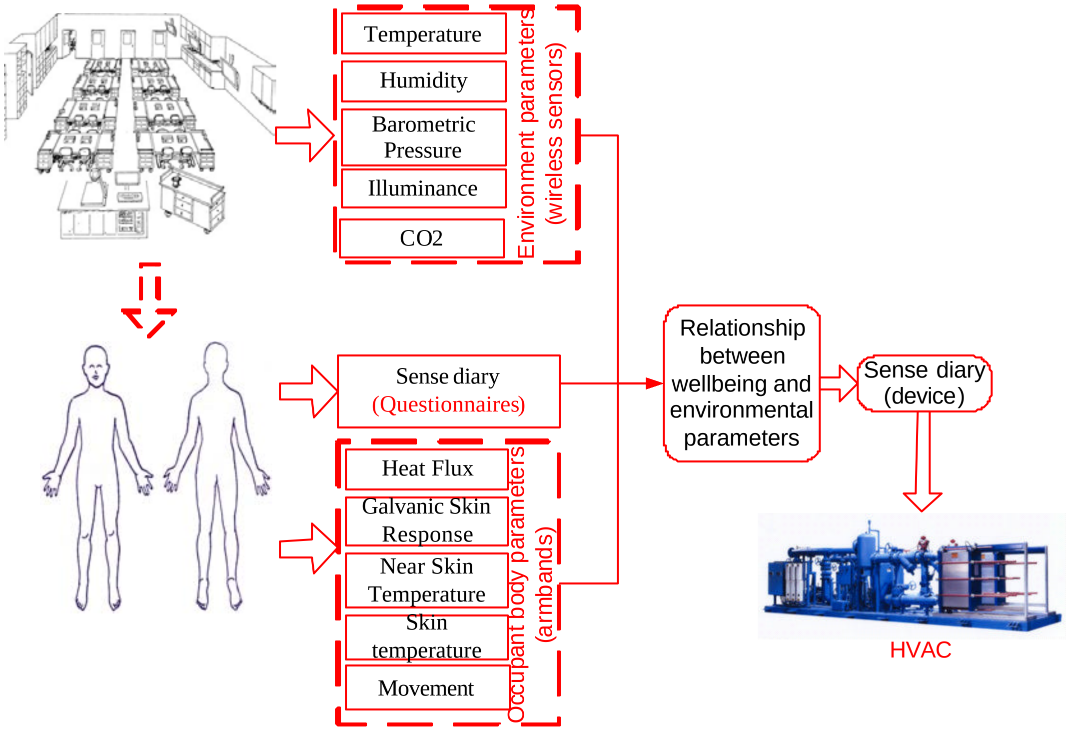

Figure 1. Research Plan

environmental parameters, and apply armbands to measure occupant's body parameters. The armbands can also be used to measure occupant behaviours through their embedded sensors. With such parameters, people are able to explore how the change of environmental physical parameters can impact on occupant body parameters such as skin temperature. As some characteristics can not be measured with sensors, we designed a questionnaire, also called ***soft sense diary*** (see Appendix). The collected data are then analysed, and relationship among variables are explored. The wireless sensor kit was bought from Crossbow (www.xbow.com), and three identical armbands from BodyMedia (www.bodymedia.com/).

The wireless sensor kit has four smaller sized sensors, each of which measures temperature and relative humidity (see Figure 2a); and two larger sized, each of which measures temperature, relative humidity, and light (see Figure 2b).

The armband measures several parameters, below lists some

- **Accelerometer** measures vertical and horizontal motion of its wearer;
- **Heat flux** measures how much heat the wearer's body is giving off.
- **Galvanic skin response** measures skin conductivity affected by physical exertion and emotional stimuli such as psychological stress
- **Skin temperature** reveals the body's core temperature trends affected by the level of a person's physical exertion or lack thereof

Figure 2a

Figure 2b

Figure 2c

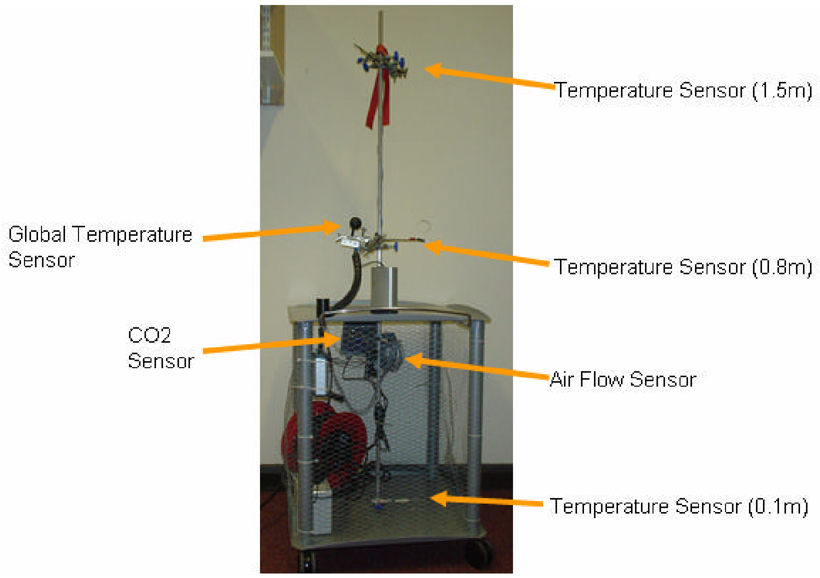

Figure 3 A sensor set

In order to collect Carbon dioxide and mean radiant temperature, a sensor set was used to measure these parameters (see Figure 3). As shown in Figure 3, apart from three temperature sensors and an air flow sensor, a carbon dioxide sensor and a global temperature sensor are installed in the sensor set.
Figure 4 shows an example of parameter distributions collected from an armband wearer. For the figure, for example, around 10:00 o'clock, there is a dramatic change in heat flux and skin temperature, this is because the armband wearer went outside in a lower temperature environment.

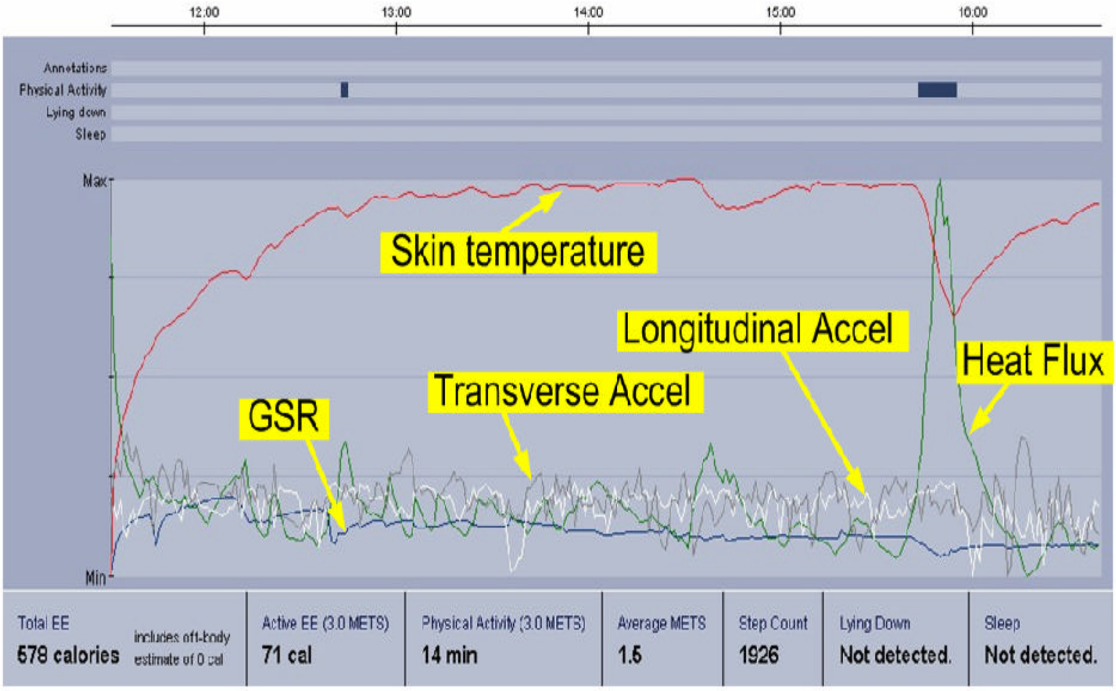

Figure 3: an example of the parameter distributions of an object

We set three day experiment in a 3m×5m office. In the experiments, objects wearing armbands were working in the office, and the sensor set and the wireless sensor kit were placed in the office. By adjusting the air-conditioner temperature one degree Celsius every 40 minutes, the temperature was changed from 16 to 28 degree Celsius.

The object profiles are listed in Tables 1, 2 , and 3.

The first experiment (8^{th} November, 2006)

Subjects	Gender	Age range	Height (cm)	Weight	Clothing
A	Female	20-25	160-165	55	0.8
B	Male	35-40	180-185	75	0.8
C	Male	45-50	180-185	80	0.8

Table 1. Object profiles in the first day experiment

The second experiment (9th November, 2006)

Subjects	Gender	Age range	Height (cm)	Weight	Clothing
B	Male	35-40	180-185	75	0.8
C	Male	45-50	180-185	80	0.8
D	Male	45-50	170-175	70	1.0

Table 2. Object profiles in the second day experiment

The third experiment (8th December, 2006)

Subjects	Gender	Age range	Height (cm)	Weight	Clothing
E	Female	45-50	170-175	75	0.8
F	Male	40-45	170-175	80	0.8

Table 3. Object profiles in the third day experiment

In a certain degree, Galvanic skin response (GSR) can reflect wearer's mood. Hence, we compare the GSR of the objects in Figure 4, from which one can see the different patterns.

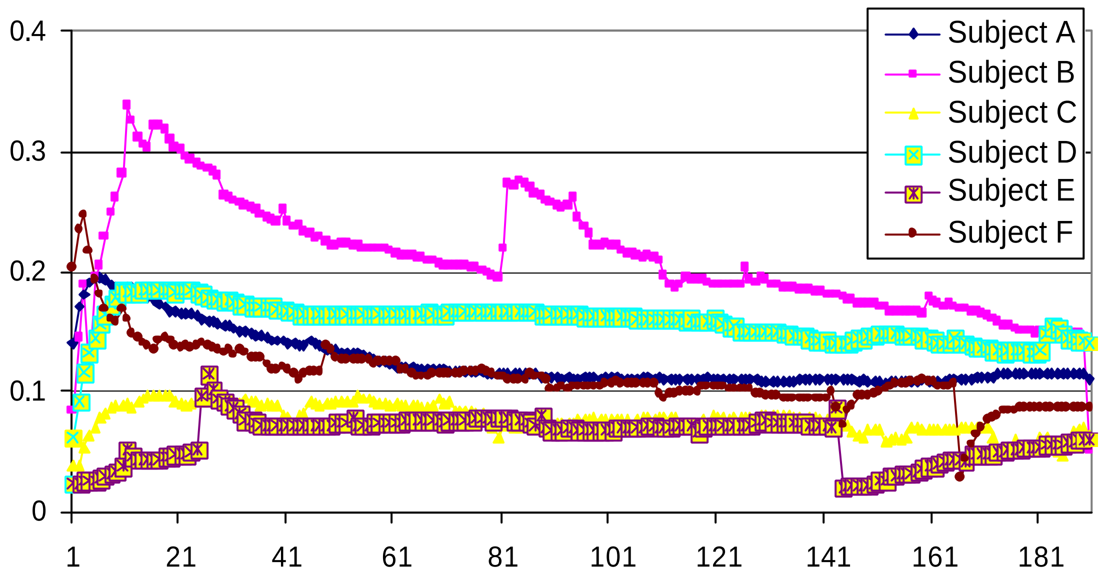

Figure 4. A comparison of GSR of the armband wearers

3. BAYESIAN NETWORK DEVELOPMENT

Through the above experiment, data were collected, and then analysed. A Bayesian network model is then built based on the data. The algorithm of building a Bayesian network model can be found from to Jensen (2001), and Neapolitan (2003).

For convenience, we borrowed a Bayesian software package developed by Cheng (2001). The Bayesian network model built on our collected data is shown in Figure 5. It shows, for example, that the Near Body Temperature (shown in *Near_body_tem* box) is a factor resulting in the

change of GSR (shown in *GSR_averag* box), while GSR is one of dependent factors to Energy Expenditure (shown in *Energy_expend* box).
The strength of the causal relationships can also be estimated from the Bayesian network models. For example, from the model, it shows that the causal relationship between Near Body Temperature and GSR is stronger than the causal relationship between GSR and Energy Expenditure.

CONCLUSIONS

Improving indoor environment to achieve a high quality living and work area can improve people's well-being and productivity.
This paper applies Bayesian networks to model the causal relationships between indoor environmental parameters and occupant's body parameters, on the basis of the data collected by a wireless sensor network, and body sensor sets.
Essentially, occupant behaviour, building services systems, indoor and outdoor environments are factors relevant to energy consumption, and occupant productivity. By revealing their relationships, it would be helpful for practitioners to design and maintain a better indoor environment for occupants.

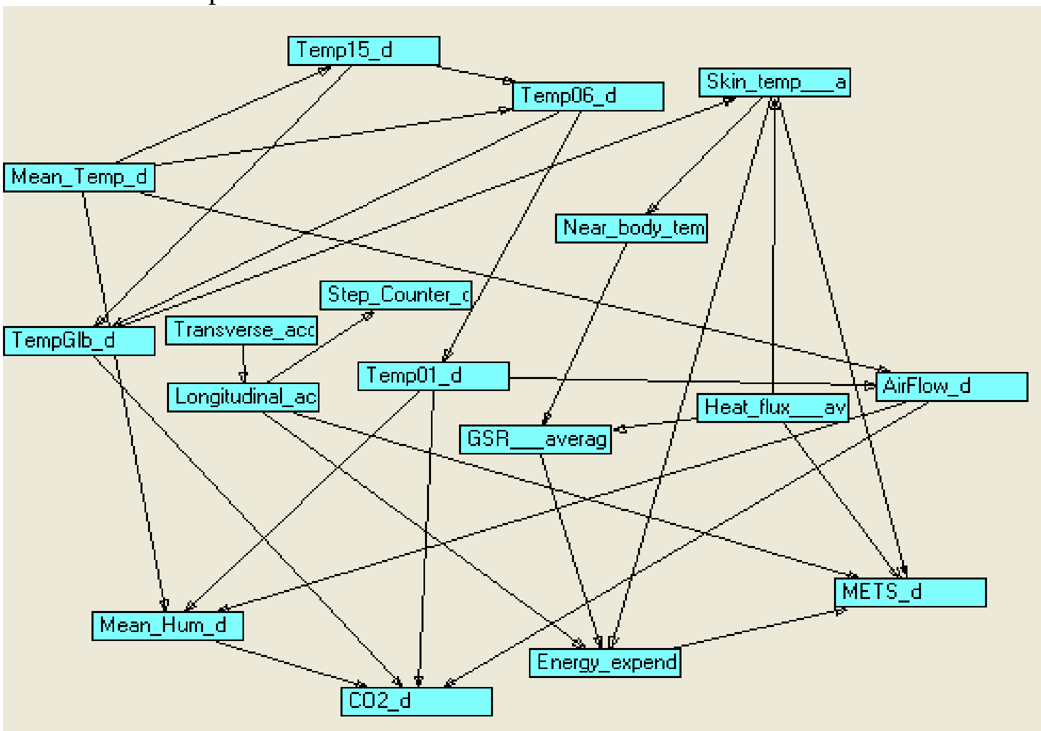

Figure 5. The Bayesian network model

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Appendix

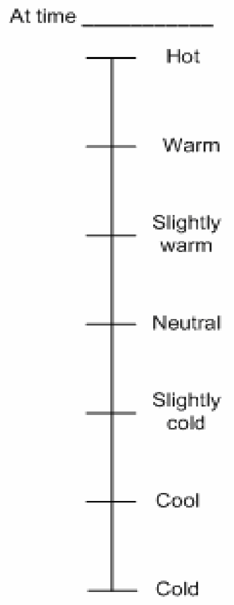
Sensors Recording Parameters of Indoor Environment and Occupiers

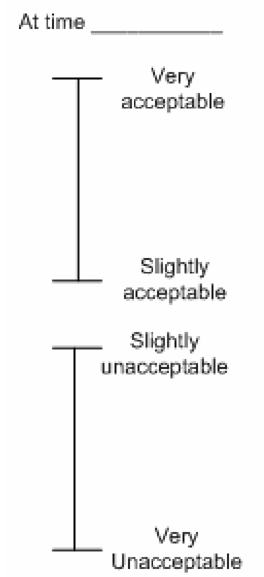
A *Soft Sense* Diary for Recording Occupant Response to Indoor Environment and Occupier Behavior

Date:__________________ Time:__________________

Comfort Data: Recording response to environmental conditions

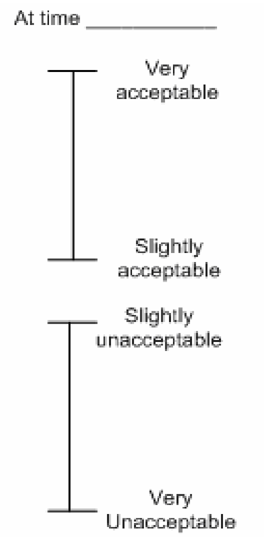
A. About the indoor temperature, I feel B. Do you feel air movement around you?





B. Do you feel air movement around you?

Yes☐ No☐



C. What is your general feeling about the office environment?

It is bad |————————————————————| It is good.

Breakfast:
No ☐ Yes ☐

Lunch:
No ☐ Yes ☐

D. About the indoor illumination, I feel
At time _________
It is too bright |————————————————| It is too dim.

E. About air quality
At time _________
Air stuffy |————————————————| air fresh

F. About air quality
At time _________
Air humid |————————————————| Air dry

Occupant behavior: Recording Actions and Activities

Entering and Leaving the Room

I leave the room, at time….. To do the following activity
___________________ _______________________

I open the door, at time
________; ________; ________; ________;

I shut the door, at time
________; ________; ________; ________;

I switch on the air conditioner, at time
________, set temperature to be ______; ________, set temperature to be ______;

I switch off the air conditioner, at time
________; ________; ________; ________;
Referring to Figure 1, your clothing unit is ____.

Occupant profiles

Age range: ______ Gender:_________

Height range ______ Weight range:_________