## Citation for published version


Wu, Shaomin and Noy, Penny (2010) A Conceptual Design of a Wireless Sensor Actuator System for Optimizing Energy and Well-being in Buildings. Intelligent Buildings International, 2 (1). pp. 41-56. ISSN 1750-8975.


## DOI


https://doi.org/10.3763/inbi.2009.0032


## Link to record in KAR



## Document Version

Publisher pdf

# A conceptual design of a wireless sensor actuator system for optimising energy and well-being in buildings

Shaomin Wu[1]
School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom

Penny Noy
38 Tradescant Road, London SW8 1XQ

**Abstract**

This paper presents a prototype model based on a Wireless Sensor Actuator Network (WSAN) aimed at optimising both energy consumption of environmental systems, and well-being of occupants in buildings. This model is a system consisting of the following components: a wireless sensor network (WSN), *Sense Diaries*, environmental systems such as HVAC (Heating, Ventilation, and Air-Conditioning) systems, and a central computer. A Multi-agent System (MAS) is used to derive and act on preferences of occupants. Each occupant is represented by a personal agent in the MAS. The sense diary is a new device designed to elicit feedback from occupants about their satisfaction with the environment. The roles of the components are: the WSAN collects data about physical parameters such as temperature and humidity, from an indoor environment; the central computer processes the collected data; the sense diaries leverage trade-offs between energy consumption and well-being, in conjunction with the agent system; and the environmental systems control the indoor environment.

Keywords: Wireless sensor networks, environmental systems, data processing, multi-agent systems.

## 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 is a group of sensors linked by wireless media to perform distributed sensing tasks. WSNs have attracted a wide interest from academia and industry alike due to their

[1] Corresponding author. Email: s.m.wu@kent.ac.uk

Suggested citation: Wu, S., & Noy, P. (2010). A conceptual design of a wireless sensor actuator system for optimizing energy and well-being in buildings. Intelligent Buildings International, 2(1), 41-56.

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.

Collecting and then processing data of indoor environmental variables—such as temperature, humidity, light—through WSNs in buildings draws a dynamic picture of the actual state of the indoor environment in the building, thus, in principle, allowing for efficient on-line control of systems, and hence providing occupants with increased well-being and less energy consumption.

By connecting a WSN to actuators in a building, we can build up a WSAN (Wireless Sensor Actuator Network). WSANs not only collect information of indoor environmental variables, but also trigger and further control the environmental systems. Such systems construct a real-time closed-loop control system, where occupants are included.

This article presents a WSAN-based prototype model, which aims at optimising both energy consumption and occupant comfort. There has been research in developing and deploying embedded control systems where wired sensors and actuators are used (Bertsekas and Tsitsiklis, 1996; Gassmann and Meixner, 2001; Ogata, 2001). However, using low-power wireless sensors fundamentally changes the nature of the problem because of the bandwidth and power limitations of these networks. Although WSNs themselves have recently been a very active area of research (Akyildiz et al, 2002; Zhao and Guibas, 2004), focus has been mainly on the sensing aspects of WSNs, instead of both sensing and the use of sensor data in controlling environmental systems.

The purposes of installing a WSN in a building are two-fold: monitoring the indoor environment in a building and then controlling it, and analysing collected sensory data to improve the design of the building and its environmental systems. The former aims at real time control, whereas the latter is for off-line analysis. This paper discusses relevant topics on the real time control.

The article is structured as follows. Section 2 discusses relevant topics on energy consumption and comfort. Section 3 presents the prototype model regarding its system architecture, databases, data processing, and control law. Section 4 describes how a multi-agent system can provide personalization, control and assessment. Section 5 discusses some challenges that might be faced in the use of the WSAN. Section 6 concludes the paper.

## 2. Optimizing well-being and energy consumption

### 2.1 Well-being

Occupant well-being includes different facets of comfort, which can be measured by various comfort indexes such as thermal comfort, visual comfort, indoor air quality, and acoustic comfort.

Normally, thermal comfort is relevant to a number of parameters such as air velocity, mean radiant temperature, people's activity, etc. The controlled variable for thermal comfort can be the predicted mean vote (PMV) index which depends upon 6 parameters (Fanger, 1972): the temperature of the zone, the relative humidity, the mean radiant temperature, the air velocity, the user's activity level and the clothing parameter. Thermal comfort has been studied on the basis of wireless sensor data in the building automation literature. For example, Malkawi and Srinivasan (2005) use wireless sensor data to build up a model which can visualize and interact with buildings and their thermal environments.

Visual comfort is relevant to a number of subjective and objective factors, which include the light levels and their spatial distribution, the glare, the colour rendering, the view, etc. The most suitable variables for controlling visual comfort are the light level, measuring lux, as all other parameters are strongly subjective and difficult to measure (Baker et al, 1993).

The indoor air quality is mainly influenced by the concentration of indoor pollutants. There is a wide range of indoor pollutants, and specific sensors are required to measure each one of them. The $CO_2$ concentration is one of the most representative controlled variables to measure the indoor air quality, as it reflects the presence of users as well.

The acoustic characteristic of a space is a critical factor for individual performance. If people are working in a noisy space, their productivity can be dramatically reduced when compared to that in a quieter space. Standards have been established for providing general comfort in building environments, for example, temperature should be 20–24 $^{o}$C, humidity 30–70%, $CO_2$ concentration 1000pm, mean brightness 500–2000 lux and so forth (ASHRAE Standard, 1992). For a more detailed discussion of well-being, the reader is referred to Clements-Croome (2005).

## 2.2 Energy consumption and occupant behaviour

Buildings are responsible for a large percentage of all national energy consumption. Table 1 shows statistics of energy consumption in buildings. According to the table, the main energy consumption in both commercial and residential buildings are heating, lighting and cooling, which can be controlled by HVAC and lighting systems. Hence, properly used, these systems can reduce energy consumption.

Table 1: Energy consumption in buildings (Interlaboratory Working Group, 2000)

| End Use | Residential (%) | Commercial (%) |
|---|---|---|
| Space heating | 6.7 | 2.0 |
| Space cooling | 1.5 | 1.1 |
| Water heating | 2.7 | 0.9 |
| Refrigerator/Freezer | 1.7 | 0.6 |
| Lighting | 1.1 | 3.8 |
| Cooking | 0.6 | - |
| Clothes dryers | 0.6 | - |
| Colour TVs | 0.8 | - |
| Ventilation/Furnaces | 0.4 | 0.6 |
| Office equipment | - | 1.4 |
| Miscellaneous | 3.0 | 4.9 |
| Total | 19.0 | 15.2 |

Energy consumption is relevant to occupant behaviour patterns. A simple example is that people preferring a higher indoor air temperature consume more energy than those who do not (when the outside temperature is lower). Another example is, people forgetting to turn off the lighting system, which wastes energy. Due to the second example, there is a widely studied approach to saving energy consumption by installing occupancy sensors which tell the HVAC and lighting systems to act according to the presence of occupants.

Recently, there has been a lot of research in understanding how the occupant behaviour impacts energy consumption and well-being. From this point of view, it will be useful if buildings and their services systems are designed with built-in devices, such as E-PROM (Erasable Programmable Read Only Memory) chips, that collect data as to how the building and building services systems are used, the environmental conditions under which they operate, etc. In addition, many companies conduct surveys in order to obtain occupant behaviour pattern information, though these are normally only undertaken occasionally. Despite the significant investment in these efforts, much of this behaviour pattern information is being under-utilised, or is not being used at all, for various reasons, including the need for new analysis methods combining different types of information.

### 2.3 Objective function

Minimising energy consumption and maximising human comfort are commonly used criteria in building automation. Cost of energy consumption might be easy to estimate in most scenarios, however, cost of comfort is hard to measure as there is not a universal standard that maps comfort to cost. Therefore, it is difficult to use one objective function that optimises both energy consumption and occupant comfort. Some researchers have built relationships between comfort and cost (Bernard and Kuntze, 2001; Kolokotsa et al, 2002; Mozer, 1998), however, the correctness and validation of these relationships need confirming by data from the real world. Some of the parameters in their utility functions are defined by the researchers themselves, but there is a need to choose weightings that can reflect the importance of different aspects so that the optimization can reflect building policy, occupant activity etc. These artificially defined parameters may vary from person to person, although they might be identical from a realistic perspective. Where the WSAN data has been used to build personal preferences of individual occupants, the utility function can be personalized.

A simplified approach is to optimise energy cost and comfort separately, by the following approach:

- if no occupancy is found, relevant environmental systems such as HVAC and lighting systems, are turned off, and no comfort is considered in this case. This reduces energy consumption, and
- if occupancy is detected, human comfort is maximised through considering occupant preference. In this case, energy consumption is not considered, though trade-offs between individual occupant preferences will be required in multiple-occupancy situations.

Comfort for all occupants is a worthy objective, but due to various comfort requirements and clothing levels among occupants, a more practical goal is assuring that at least a proportion, say, 80%, of each individual occupant's preferences are satisfied..

## 3. System architecture

A WSAN system can be designed to optimise both energy consumption and occupant comfort. From a system function's perspective, the system has four subsystems:

**Hardware architecture** a wireless sensor network that monitors PPIE (physical parameters of indoor environment). Actuators control the PPIE through environmental systems. A sense dairy takes the current sensor values and selects a setting to the actuators to fulfill the users' preferences, on the basis of a specified control law. In addition to monitoring PPIE, the sensor network can monitor occupancy in the building to optimise HVAC and lighting settings to reduce energy consumption and to build individual preference profiles.

**Databases** The database contains a set of preferred PPIE, and health (battery level etc.) of sensors;

**Data processing** involves approaches to analysing data received from sensors, comparing the sensed information to the preferred PPIE, and then making a final suggestion to trigger the actuators. A multi-agent system (MAS) can be used to personalize the environmental conditions automatically, based on profiles learned from the combination of sensor and sense diary data.

**Control law** defines the way to control the indoor environmental systems according to the suggestions made from the data processing.

The details of the system is shown as follows.

### 3.1 Hardware system

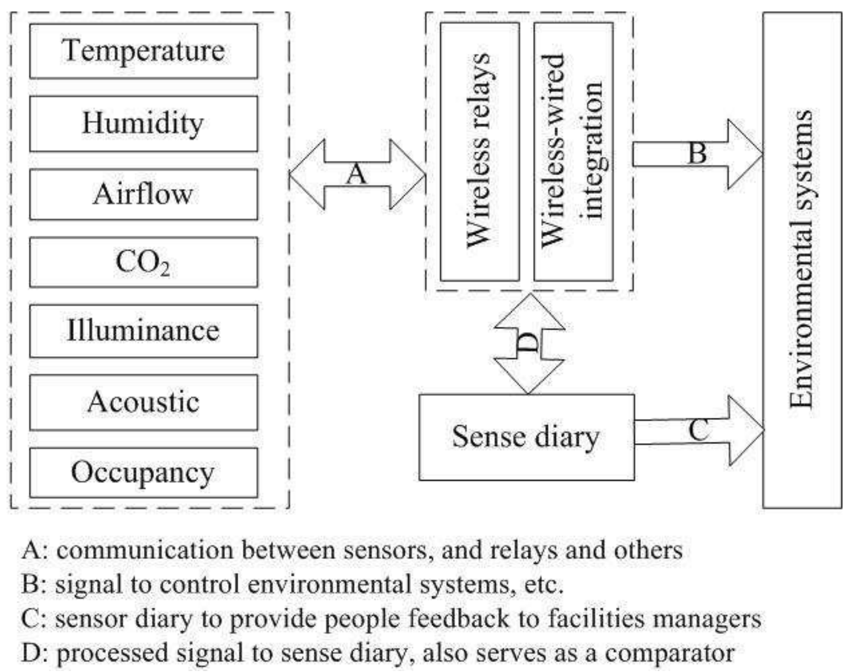


Figure 1. System Architecture

The whole system is made of five subsystems: sensor, integration, sense diary, actuator and computational sub-systems.

**Sensors** Wireless sensors are installed to measure the following physical variables:

**(a)** mean radiant temperature, and indoor temperature;

**(b)** relative humidity;

**(c)** air velocity;

**(d)** $CO_2$ concentration;

**(e)** light ;

**(f)** acoustic;

**(g)** occupancy

The sensor data can be used in a variety of ways.

The sensors (a) to (c) are used for the evaluation of the thermal comfort using the Fanger's PMV (Fanger, 1972). Information about temperatures in buildings is also of importance in assessing the value of various energy conservation measures and gives an indication of the standards of thermal comfort enjoyed by the occupants.

The sensor (d) evaluates the indoor air quality and the sensor (e) is used for the measurement of indoor visual comfort.

Acoustic sensors (f) are used to improve the occupant's acoustic comfort working in a space. The acoustic characteristic of a space is a critical factor for productivity. To attain adequate elimination of noise disturbances in open office environments, a background noise masking system that increases the acoustic isolation of the work station can be installed. In some cases, the purpose of using the acoustic sensors might be very simple, for example, *keep the indoor environment quiet (say, do not run the noisy vacuum cleaner) when I am watching TV*.

Occupancy sensors (g) reduce energy waste. When no occupancy is detected by occupancy sensors for a given time period (for example, 15 minutes), the HVAC system and lighting system can be turned off (assuming this is an efficient way to deal with, for instance, the air conditioning system). When occupancy is again detected, the HVAC system and lighting system resumes operation as set by the user preference. The occupancy sensors are very useful, especially for the case when people are unlikely to remember to turn lights off, an occupancy sensor is a great way to save money. Although cost of the occupancy sensors varies by the type of sensors used, occupancy sensors can usually pay for themselves through energy savings within a few years of use. Thus, in most cases, occupancy sensors offer greater energy savings and more flexibility than other forms of control, and they have proven to work effectively in a variety of applications.

**Integration system** This system includes relays, and functionality that integrates wireless sensors with wired systems (other sensors, or PCs providing web interfaces). Examples of protocols used in the systems are Zigbee, or LonTalk. *ZigBee* provides a suite of high level communication protocols using small, low-power digital radios for wireless personal area networks. *LonTalk* is a control protocol for networking devices over a variety of media (twisted pair, fiber optics, radio frequency) popular for automation of systems such as lighting and HVAC in building systems.

**Sense dairy** Croome (1990) introduced the concept of a Sense Diary, which has two functions: pre-specifying occupant's preference, and trigger actuators according to preferences. The triggering may be direct, or via a system, such as a MAS, which builds individual profiles and negotiates changes with building policy components. A sense dairy integrates functions in a control panel, and, in this example, four variables are displayed and controllable. Figure 2 shows a prototype of the sense dairy. The following controllable physical variables are designed in the sense diary.

- temperature
- light

- sound
- air quality

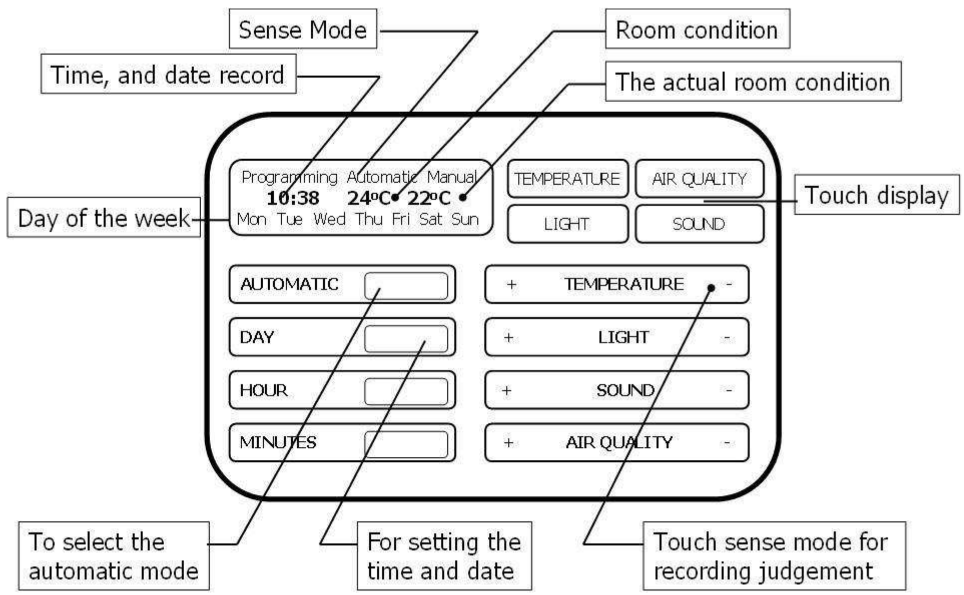


Figure 2. Sense Diary

**Environmental systems with actuators and actuator state sensing** The environmental systems such as HVAC (heating, ventilation, air-conditioning systems), are targeted for adjusting. The environmental systems are controlled through actuators, which includes

- Relays for HVAC systems and the electric lighting systems
- Window opening/closing motors
- Shading opening/closing motors, and
- Noise masking system adjusting.

Information about the state of the actuators and the change of state resulting from an interaction with the occupant (e.g. turning the light on, opening a window) is required to learn the occupant's preferences in a system where the occupant still has manual control. (Note, it is assumed that the occupant will maintain manual control as well as there being automatic control. This provides another input for the system to learn the occupant's behaviour from, but it is also considered desirable for the occupant retain a level of manual control.)

### 3.2 Database systems

Five databases are designed for the application and are shown in Figure 3.

**Sensor data database** This database stores raw data received from the wireless sensor network. This database contains two tables, environmental parameter table, and sensor health (status) table. The environmental parameter table stores variables such as temperature, humidity, light, $CO_2$ concentration, air flow, and energy power readings. The sensor health table has the following variables:

- time stamped readings from the sensors

- health status of individual sensors, e.g., battery status, battery voltage
- network parameters, connectivity and routing information
- sensor location: geographical location of the sensors should be recorded

**Processed data** This stores the data from the data pre-processing phase which is discussed in section 3.3.

**Pattern database** The database contains patterns derived from the pre-processed sensor data. Machine learning can be used to find patterns which match both human behaviour and energy consumption. The patterns can be if-then rules, comparators, and other types of knowledge. The patterns can be general or specific to individuals, therefore giving their environmental preferences.

**Policy database** As information from briefing, and building management systems, are important, the fourth database is used to store existing information.

**Suggestion database** By comparing information from the Policy database and the Pattern database, final suggestions on how to save energy and improve well-being can be stored in the suggestion database.

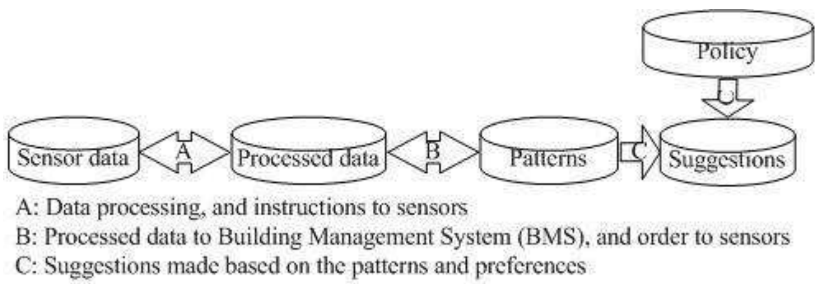


Figure 3. Databases

### 3.3 Data processing

The whole processing process is shown in Figure 4. It is divided into four phases: data acquisition, data pre-processing, pattern recognition, and suggestion making. MAS techniques can be used at all stages, but particularly in building personal preferences, or profiles, in resolving conflict between occupant profiles, and in comparing requests against policy to balance well-being and energy conservation.

**Data acquisition** Signals from sensors are multi-variate time series; therefore, the frequencies of sampling the signals — or sampling rates — should be given prior to collecting data from the sensors. Sense diary elicitation rate also needs setting. Actuator interaction (change of actuator state) and presence data is usually recorded when a change occurs, such as a person entering a room, or switching on a light.

**Data pre-processing** This phase is needed to complete data preparation, which first focuses on cleansing data.

1. *Data re-sampling* As one mote might sense several physical parameters with the same sampling rate, there is a need to re-sample data from the raw data. Instances for depicting human behaviour patterns can be produced by sampling different variables. For example, instances can include temperature sampled sensory data from every 10 minutes, humidity from every 30 minutes and so on.

2. *Data cleansing* Checking data validity is an important step to ensure data quality. For example, indoor temperature commonly lies in a certain interval, data beyond this interval should be removed from the database. Meanwhile, removing noise, smoothing time series, handling missing data and incomplete data, might be needed in this step. A malfunction flag needs to be issued if a significant degree of error is encountered.
3. *Data abstraction* Some analyses will require abstractions of the data, which can also reduce the amount of data needed to be stored.

**Pattern recognition** Pattern recognition techniques can be applied to find useful patterns from the processed data. The main task in this step might be to learn the distribution of occupant activities. One should understand that predicting occupant behaviour—*what will the occupant do in the next few minutes*, say—might be hard. For example, research shows that different users not only have different preferences from one another, but also have widely varying lighting preferences for different tasks (Granderson et al, 2004). Apart from predicting requirements, the data is used for learning the preferences of individual occupants.

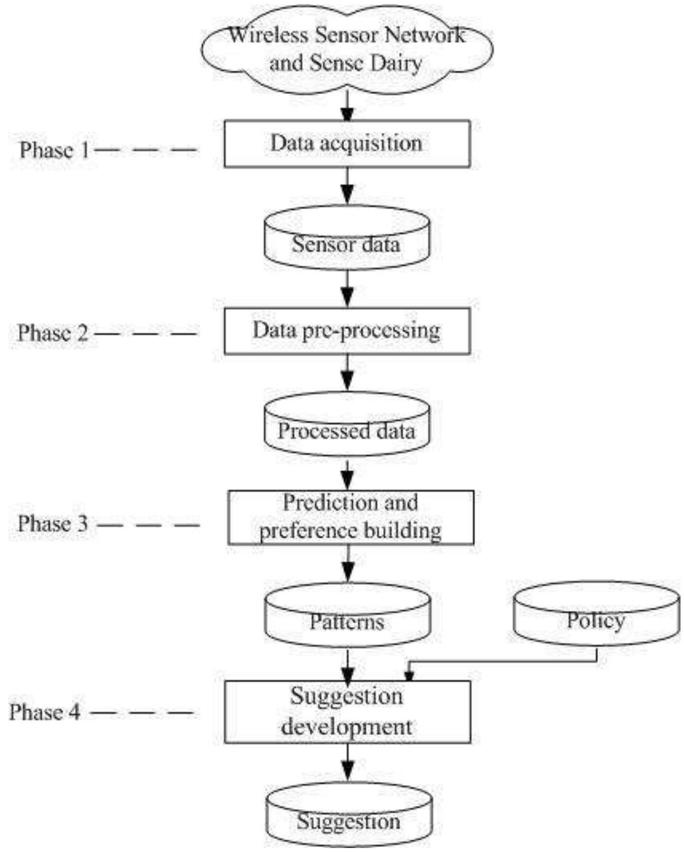


Figure 4. Data processing from sensing to suggestion

Below we give an example of data cleansing for a dataset sensed from the real world by a WSN.

**Example** *(Wu and Clements-Croome, 2007) The data are collected from 54 wireless sensors in their lab for collecting information of temperature, humidity, and light from*

*28th February and 5th April, 2004 (Intel Berkeley Research Lab, 2004)). The original dataset has 2313682 observations, and 8 variables: date, timestamp, epoch, moteid, temperature, humidity, light, and battery voltage. Epoch is a monotonically increasing sequence number from each mote. Two readings from the same epoch number were produced from different motes at the same time. Moteids, ranging from 1-54, are identities of wireless sensors. Temperature is in degrees Celsius. Humidity is temperature corrected relative humidity, ranging from 0-100%. Light is in Lux. Voltage is expressed in volts, ranging from 2 to 3. The following steps shows that the quality of the data is fairy poor.*

- **Working time:** *If one is concerned with the indoor environment only within working time, and assume that the working time is from 8:00 to 18:00, then 1365866 are ignored, and 947816 instances left.*
- **Invalid motes:** *The 54 motes are labelled with 1 to 54 in the dataset, that is 1≤moteid≤54. Hence, if we delete all of the instances beyond the interval 1≤moteid≤54, 3695 instances can be removed, and 944121 instances left.*
- **Invalid temperature:** *Assume the temperature in the building range from 10 to 40 degree Celsius. Using this condition, 169428 instances are removed, and 774693 instances are left.*
- **Invalid humidity:** *As indicated in (Intel Berkeley Research Lab, 2004), the humidity lies in 0-100%, using this condition, no instance is removed;*
- **Invalid light:** *Set light>0, then 23654 instances are removed; and 751039 instances are left;*
- **Invalid voltage:** *Set 2≤voltage≤3, then 167 instances are removed and 750872 instances remains.*

Having the above check, we have an impression that the original dataset has a large amount of invalid observations, or in data mining terminology, the dataset is very dirty.

### 3.4 Control law

When a quantity, such as temperature, must be made to behave in a desired manner over time, control methods are used. Other examples in the automatic pilot of an aircraft that maintains speed, altitude and heading, or the cruise control in a car, which maintains constant speed independently of road inclines. Where control is automatic, as in these examples where control is not undertaken by a human, the system implements a decision process, also called the control law, that dictates appropriate control actions. Decisions are made based on how different the actual temperature is from the desired one, and knowledge of the room's response to heating and ventilation increases and decreases. This knowledge is often captured in a mathematical model. These systems are described as closed-loop feedback control systems, because information about the actual system behaviour is fed back to the controller. Information about the actual environmental conditions is fed to the controller from sensors, control decisions are implemented by means of actuators that, for instance activate the boiler to raise the circulating water in radiators.

Control systems can be viewed in a broader sense, for instance planning and expert systems can be seen as decision processes. Intelligent control methods are being developed for systems that cannot be described by traditional mathematical equations;

fuzzy control logic and neural networks are examples of other methodologies being applied. In our case the mathematical model of the behaviour of the actuators and the thermodynamics of the environment needs to be enhanced by making predictions about future demand (predicting occupancy and outside temperature), optimizing individual occupant working environments, as well as resolving conflict between individual preferences (aside from the actual building and constant updating of preferences). Another variable input to the decision process is the building policy which affects what is allowed (e.g. how high a temperature), desired (balance level between energy conservation and well-being), and required (that the temperature lies within legal working limits).

In our application, WSNs, actuators, sense dairies and occupants make up such a closed-loop control system. However, actuators do not need to respond with every change of the signal from the WSN. For example, a temperature sensor collects data every minute, however, the state of the air conditioning does not need to change every minute, although the data from the temperature sensors changes frequently.

A simple control law for this scenario can be set as follows:

- **Policy instantiation:** For a given situation, based upon the current occupant or occupants, their available preferences, and the building policy, settings are derived (possibly by negotiation) and corresponding demands made from the actuators.
- **Energy optimisation:** Occupancy sensors are responsible for energy saving: when no occupancy is detected, relevant energy-consuming systems can be shut down (or reduced based upon probability of return of occupant).
- **Comfort optimisation:** Only if a change larger than a certain threshold, or a change point, is detected by other sensors (for example, temperature sensor, light sensors), the relevant actuators are activated.

## 4. Multi-agent system for personalization, control and assessment

This section discusses why agent technology is suitable for this application, how personal agents can represent the occupants of the building (and perhaps other stakeholders as well), and the use of multi-agent systems for control and assessment (of energy conservation and level of well-being achieved).

### 4.1 Why agents?

A software agent is a computer program that acts for a user or other program in a relationship of agency. It can be differentiated from an ordinary program (or set of programs) by being characterized by reactivity to the environment and other agents, autonomy, goal-orientation, and persistence (Franklin and Graesser, 1996). However, every agent may not display all of these characteristics, as the term is also often applied quite loosely. A personal agent, which carries out tasks automatically for the user, is one of a number of different types of agents. In general terms, a multi-agent system (MAS) (Wooldridge, 1999) is a collection of software agents capable of reaching goals that are difficult to achieve by an individual system.

There are several reasons why agent technology is valuable for this application. Firstly, agent-oriented computation is useful as a way of thinking about complex problems. Secondly, there are specific aspects of this problem that lend themselves to agent application:

- Distributed nature of the problem;
- Parallel processing aspect (local/global analysis);
- Natural, intuitive solution, since we want to represent people in the system; and
- Real-time decision making as well as complex off-line analysis

The environment of an intelligent building is also, potentially, inaccessible, non-deterministic, non-episodic, dynamic and continuous (Rutishauser and Schäfer, 2002), making it of a most complex type (Wooldridge, 1999) for which agent systems are particularly useful. For example, Lou Maher et al (2005) use agent and sensor technologies to support collaborative design in 3D virtual worlds in building design.

### 4.2 Personal agents

In order to optimize well-being of occupants and energy use in buildings, it is necessary to increase the involvement and representation of the occupant in the building. Involvement, because it is necessary for occupants to understand and interact with the building management system for efficient operation (Meir and Hare, 2004). Representation, because our aim is to understand better the individual occupant's requirements and better satisfy these. (We seek greater representation of *all* humans, including other stakeholders - see Section **Error! Reference source not found.**.)

In addition, it may emerge that closely controlled environments are desirable for maximizing energy conservation in a carbon-taxed future world[2]. If this is the case, then it must be recognized that such environments represent a loss of control to the occupant, so that their input to the control mechanism (agent system) is imperative. They need to experience their **direct** control having been replaced by **indirect** control, so that they trust, and have confidence in, the system.

Another aspect to this personalization is the study of individual requirements. It is currently not known whether individual requirements or tolerances vary greatly from the standard ranges, or whether there are distinct classifications of different requirements within the ranges. This system also presents an opportunity to study the sensitivities of individuals, suffering, for example, hay fever, in such environments, and, for a significant minority, thus provide the information required to substantially improve their health and well-being.

A number of ways that people can be represented in the system can be identified:

- Via sensors
- Touch screen (Sense Diary), on-line, or paper questionnaire
- Profile manually set (learning by the person)
- Profile learned by system - using sensor data of the environment, and sensed interactions with the actuators. (The system cannot learn from the sensors alone, see following paragraph.)
- Activity log, access to Outlook calendar etc

[2]On the other hand the most energy-efficient, intelligent buildings may turn out to be *low-tech*. If so, we still envisage importance for a version of the system presented here, where the actuators are not included. The sensor network can be used for assessment purposes, determining individual preferences etc., and may, perhaps, demonstrate that such buildings are more energy efficient.

In general, the software agent can use the sensor data to build a *profile* of the occupant's *preferences*, or to *predict* the occupant's next requirement (behaviour) in terms of presence/absence and activity.

The minimum requirement for building a profile is sensor data about the environment and the interactions the people have with their environment, or the feedback from the occupant of how they are perceiving and experiencing their conditions, i.e. their assessment and their physical response. This feedback can be active, on the part of the occupant, as in entering information on a device such as the Sense Diary described in this paper, or passive where it is gained from devices for measuring heart rate etc., or indirectly derived by data from changes in behaviour, such as can be measured using tactile materials.

### 4.3 Multi-agent system for control and assessment

The multiple personal agents representing the occupants can request changes to the environmental parameters based upon the profiles of their occupants (which can be learned from data as described above, or directly entered by the user). These requests can then be examined by agents representing the room or building, and controls activated if the requests are permitted within the building management system policy. These, or other, agents can also resolve conflicts between contradictory requests from multiple-occupant spaces, or personal agents can negotiate between themselves to modify their requests, as humans generally do in such situations. However, the building management system is coarse-grained and we want to add a fine-grained layer which can respond to changing circumstances and embed detailed allowed behaviours to provide a more responsive system. This layer is an extension of the policy given by the building management system.[3]

Assessment of the behaviour of the system is relevant from two points of view:

- For the building manager to assess how well individual occupants' needs are being met (and how this relates to productivity, for instance), and how energy is being used in the building (where it is being wasted, for instance).
- For the occupant to get feedback on the same issues, and to be able to input other information, such as what their goals are, their priorities such as health, concentration requirements, or personal energy saving. In a world which may soon be allocating personal carbon allowances (Boardman et al, 2005), this feedback may become of great importance.

### 4.4 Other stakeholders

Other stakeholders, such as those directly involved (facilities managers, owners, architects etc.) and those indirectly involved (local people, government bodies etc.), are represented in the system to a greater or lesser extent, explicitly or implicitly. These stakeholders create the policy of the operation of the building and criteria for assessment of well-being, energy efficiency and general sustainability.

[3]This assumes that the agent system is not contained within the building management system, though it may be at some future point if agent applications become widely validated.

### 4.5 Agent system

An overview of the MAS is given in Figure 5. The black arrows indicate feedback to the various stakeholders of information and recommendations as appropriate. Broadly speaking, the agents are divided into personal agents representing the occupants and building agents representing the building, including assessment and control. However, some of the building agents could also be used to represent people such as the facilities manager, owner, health and safety officer etc. We will investigate the extent to which persistent (i.e. beyond the design phase) representation of the different stakeholders is desirable. This description assumes a work rather than a domestic environment. A similar system is equally valid, but in this case the facilities manager, owner etc., is also one of the occupants.

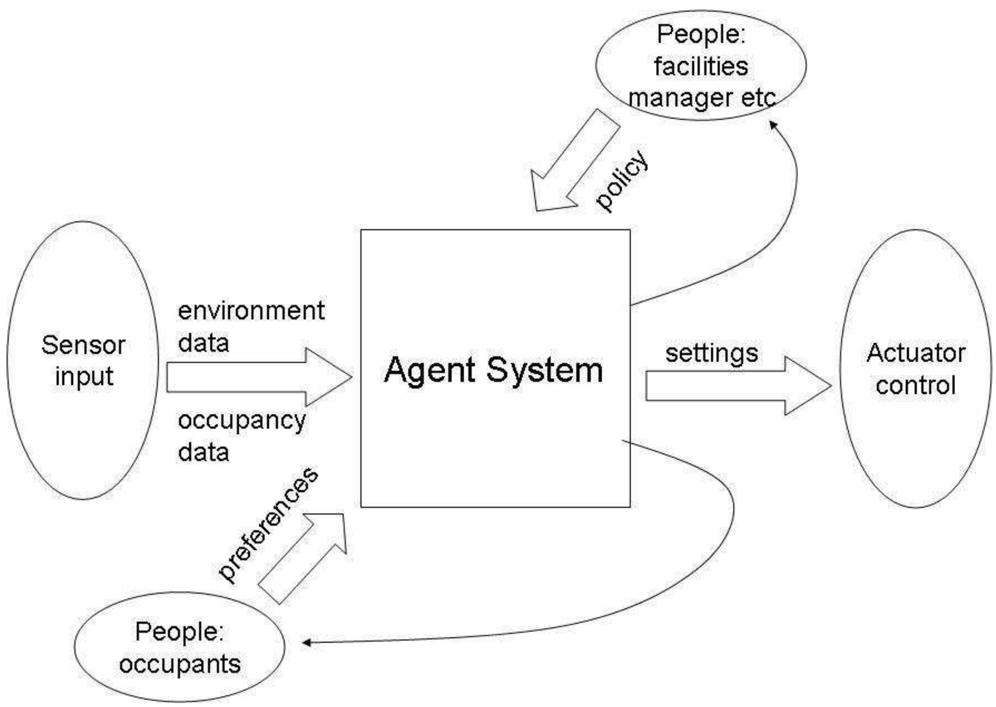


Figure 5. An overview of the multi-agent system

Existing systems focus largely upon the horizontal process only, from sensors to actuators, thus regarding the occupant and other stakeholders as passive from the point of view of the system. These systems are largely agent-based, though there is a complication of the difference between hardware and software agents, so that some do not involve a MAS based upon personal agents as described in this paper. For more discussion on other systems and the design issues of personalizing intelligent buildings see Noy et al (2006).

## 5. Challenges

This section discusses challenges presented within the sensor network and computational parts of the system.

### 5.1 Sensors

In spite of the diverse applications, sensor networks pose a number of unique technical challenges due to the following factors:

**Untethered:** The sensor nodes are not connected to any energy source. There is only a finite source of energy, which must be used for processing and communication. An interesting fact is that communication dominates processing in energy consumption. Thus, in order to make optimal use of energy, communication should be minimised as much as possible. For example, larger sampling rates can save sensor energy than smaller ones. For this reason, optimising sampling rates is one of approaches to saving energy.

**Noisy sensory data:** Sensory data is subject to several different sources of errors. In general, these sources of errors can be broadly classified as either systematic errors (bias) or random errors (noise). The main sources of noise are

- noise from external sources,
- random hardware noise,
- inaccuracies in the measurement technique (i.e., readings are not close enough to the actual value of the measured phenomenon),
- various environmental effects and noise.

### 5.2 Computational aspects

Computational challenges arise from a number of aspects as follows:

**Derivation of profile:** The sensors provide information about the environmental parameters, whether a certain person is present or absent, and their interactions (if any) with the actuator controls. Data may also be derived from the occupant directly in the form of assessments of their environment from a device or interface such as the Sense Diary. From the collected data, a profile of an occupant's preferences needs to be derived which, given a particular state of the environmental variables, predicts the user's desire for a change, or not, and puts this prediction into effect. This is challenging as the occupant's actions are inconsistent and will change over time.

**Elicitation and embedding of norms:** The policy of the building is derived from various sources: health and safety regulations; energy efficiency targets; and productivity and work environment targets set by the facilities manager (in an interpretation of instructions from the organization's owner or senior management). This policy provides constraints and goals for the agent system. Some of this policy is clearly defined, but other aspects are based upon generally accepted norms of behaviour, which may not previously have been articulated. These norms need to be visibly captured, embedded in the system and evolved over the system's lifetime.

**Utility function:** Utility functions are often used in agent systems for an agent to decide upon a course of action, where the course of action involves a number of parts (Wooldridge, 1999). Essentially, the values to the agent of the individual parts are summed to give an overall value, described as the *utility* (value) of that combination. (The inverse of the utility function can be described as a *cost* function.) The agent then chooses the option with the highest utility. In the personalization of building environments using an agent system, the question is, how can energy conservation be balanced with well-being, since well-being has a cost in energy terms? A utility function can be used for this, if a monetary measure for different aspects of well-being can be established. The cost of loss of productivity due to lack of creativity, concentration, comfort and health has been demonstrated by much research (Clements-Croome, 2005). Thus the challenge is to turn this into a cost in terms of money, so that well-being and energy consumption can be compared. Then a cost (utility) function can be defined which is a sum of the different costs (benefits), the individual costs can be given weightings, which can be varied according to the building, and individual occupant policy.

**Uncertainty:** There are a number of aspects of uncertainty in the system, which have an impact upon the design and operation of the system.

- External factors such as outside temperature and sunlight
- Future activities and presence or absence of people
- Different ways in which a particular environmental request can be met. For instance, opening a door or window to increase air flow.

**Interaction design:** The system may be reducing the amount of manual control that is available and it is collecting data about the occupants. What are the issues that will govern whether people will use the system? Will they trust and like the system? Some research has indicated that many projects designed to provide optimal conditions with minimum energy input are rarely used properly (Meir and Hare, 2004), to the extent that systems are changed or dismantled. How can this be avoided?

## 6. Conclusions

As the business environment becomes increasingly more competitive, it is essential that all available resources are used optimally and effectively. It is also necessary to find ways to use technology to reduce energy because of increasing concerns about the effect on the environment of global warming. The need to evaluate various comfort indexes in different parts of a building is becoming increasingly important, as those indexes directly and/or indirectly, affect people's well-being in the building, which influences productivity, creativity and health.

Using wireless sensor networks to collect data about the indoor physical parameters is a promising approach as wireless sensors are becoming cheaper, and easy to install.

This paper presents a prototype model that optimises energy consumption and occupant well-being in buildings. The paper discussed the following five aspects.

*Hardware architecture.* This is composed of three subsystems: (1) wireless sensor networks used to collect/sense environmental parameters and transfer them to the sense diary; (2) the sense diary used to analyse the received data, generate outputs to control the environmental systems, to input occupants' feedback and to set preferences; (3) the environmental system including energy consumption systems such as HVAC.

*Databases* Data in the prototype model can serve various purposes and need to be stored in different tables/databases. The databases can be sensor data, processed data, pattern, policy and suggestion databases. These databases are used to stored data collected from the sensor networks, occupant behavior patterns, and control laws.

*Data processing* As the data can accumulate huge amounts of data, advanced and comprehensive data analysis tools are required to process the data stream.

*Control law* This relates to optimise energy consumption on the basis of occupant behavior and occupant comfort in buildings. A simple control law can include a couple components such as policy instantiation, energy optimisation and comfort optimisation.

*Multi-agent technology* For office buildings, each occupant might have his/her own behavior pattern different from others. Multi-agent technology can be used in control and assessing energy conservation and level of well-being based on personalised information about occupant individual behaviour and comfort. It can also be used to negotiate compromises between different occupant requests, and between occupant profiles and building management policies.

In overall terms, this type of system provides methods of representing the stakeholders in the automatic operation of building systems. There are three means by which this is achieved - by direct input of policy or preferences, by real-time feedback from occupants, and by learning of patterns from collected data. This is particularly important to ascertain whether buildings designed to operate in a certain way, from the point of view of energy consumption as well as occupant comfort, do indeed deliver on their promises. However, it is also useful to assist in the study of differences in preferences between individuals, and in understanding the human interaction issues which have prevented some well-designed automatic systems from being successful.

This paper has demonstrated the value in developing this type of system. However, the complexity of such systems means that implementing them for research purposes requires significant resources, particularly if scaling beyond one or two rooms with few occupants. However, the separate aspects of the system would all benefit from further research, so it is recommended that, in addition to establishing more projects for complete systems, the design is decomposed and more projects developed to look at the separate aspects, exploring uses for the Sense Diary, developing utility functions, deriving comfort profiles from sensed data, and so on. It is also recommended that groups already with test rooms, or those in the process of designing them, adopt a modular approach so that other teams can contribute to particular modules.

**Acknowledgements**

This work was partly funded by EPSRC (The principal investigators of the project: Professor Derek Clements-Croome and Professor Kecheng Liu at the University of Reading).

## References

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., Cayirci, E., 2002. Wireless sensor networks: a survey. Computer Networks 38 (4), 393–422.

ASHRAE Standard, 1992. Ashrae standard 55-1992.

Baker, N., Fanchiotti, A., Steemers, K., 1993. Daylighting in Architecture: A European Reference Book. James & James, UK.

Bernard, T., Kuntze, H. B., 2001. Sensor-based management of energy and thermal comfort. In: Gassmann, O., Meixner, H. (Eds.), Sensors in Intelligent Buildings. Wiley-VCH.

Bertsekas, D., Tsitsiklis, J., 1996. Neuro-dynamic programming. Athena Scientific, Belmont, Massachusetts.

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C. N., Palmer, J., Sinden, G., 2005. 40% House, Environmental Change Institute Research report 31. Tech. rep., Environmental Change Institute, Background document L: Personal Carbon Allowances, Tina Fawcett.

Clements-Croome, D., 2005. Creating the productive workplace. Taylor and Francis.

Croome, D. J., 1990. Building services engineering –the invisible architecture. Building Services Engineering Research and Technology 11 (1), 27–31.

Fanger, P. O., 1972. Thermal comfort. McGraw-Hill, New York.

Franklin, S., Graesser, A., 1996. Is it and agent, or just a program? : A taxonomy for autonomous agents. In: Third International Workshop on Agent Theories, Architectures, and Languages. Springer-Verlag, pp. 139–144.

Gassmann, O., Meixner, H., 2001. Sensors in intelligent buildings. Wiley-VCH.

Granderson, J., Agogino, A. M., Wen, Y., Goebel, K., 2004. Towards demand responsive intelligent daylighting with wireless sensing and actuation. Submitted to IESNA.

Intel Berkeley Research Lab, 2004. http://db.lcs.mit.edu/labdata/labdata.html, accessed in May 2009.

Interlaboratory Working Group, 2000. Scenarios for a clean energy future. Tech. rep., Oak Ridge, TN; Oak Ridge National Laboratory and Berkeley, CA; Lawrence Berkeley National Laboratory.

Kolokotsa, D., Stavrakakis, G. S., Kalaitzakis, K., Agoris, D., 2002. Genetic algorithms optimized fuzzy controller for the indoor environmental management in buildings implemented using plc and local operating networks. Engineering Applications of Artificial Intelligence 15 (5), 417–428.

Lou Maher, M., Liew, P.-S., Gu, N., Ding, L., 2005. An agent approach to supporting collaborative design in 3d virtual worlds. Automation in Construction 14 (2), 189–195.

Malkawi, A. M., Srinivasan, R. S., 2005. A new paradigm for human-building interaction: the use of cfd and augmented reality. Automation in Construction 14 (1), 71–84.

Meir, I. A., Hare, S., 2004. Where did we go wrong? POE of some bioclimatic projects, Israel. In: Proceedings of Windsor Conference - Closing the Loop: Post-Occupancy Evaluation: The Next Steps.

Mozer, M. C., 1998. The neural network house: an environment that adapts to its inhabitants. In: (Ed.), M. C. (Ed.), Proceedings of the American Association for Artificial intelligence Spring Symposium on Intelligent Environments. AAAI Press., Menlo Park, California, pp. 110–114.

Noy, P., Liu, K., Clements-Croome, D., Qiao, B., 2006. Design issues in personalizing intelligent buildings. In: Proceedings of 2nd International Conference on Intelligent Environments, Athens, July 5-6. IET.

Ogata, K., 2001. Modern control engineering. Prentice Hall, Upper Saddle River, NJ.

Rutishauser, U., Schäfer, A., 2002. Adaptive building automation - a multi-agent approach. http://www.urut.ch/pdfs/abi1_0_0.pdf

Wooldridge, M., 1999. Multiagent systems: a modern approach to distributed artificial intelligence. MIT Press, Cambridge, Massachusetts, Ch. Intelligent Agents.

Wu, S., Clements-Croome, D., 2007. Understanding the indoor environment through mining sensory data — a case study. Energy and Buildings 39 (11), 1183–1191.

Zhao, F., Guibas, L., 2004. Wireless sensor networks: an information processing approach. Morgan Kaufmann.