A SENSOR BASED INTELLIGENT BUILDING ASSESSMENT MODEL

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Abstract: While building provides shelter for human being, the previous models for assessing the intelligence of a building seldom consider the responses of occupants. In addition, the assessment is usually conducted by an authority organization on a yearly basis, thus can seldom provide timely assistance for facility manager to improve his daily facility maintenance performance. By the extending the law of entropy into the area of intelligent building, this paper demonstrate that both energy consumption and the response of occupants are important when partially assessing the intelligence of a building. This study then develops a sensor based real time building intelligence (BI) assessment model. An experimental case study demonstrates how the model can be implemented. The developed model can address the two demerits of the previous BI assessment model.

Keywords: Building intelligence; assessment; entropy; sensor; real-time

1 Background

In the last two decades, intensive research has been done in the area of intelligent buildings (IBs) (Gassmann and Meixner, 2004). An IB is defined as a building that can meet the needs of occupants and business, and be flexible and adaptable to deal with changes (Clements-Croome, 2004; 2006). One important topic in IB research is building intelligence assessment, as the assessment may provide standard methods to evaluate new and existing building design, and assist the building manager in monitoring the 'health' of the building as well. The available IB assessment systems include the IB Rating (2002), Building Intelligence Quotient (IQ) Rating Criteria (CABA, 2004), IB Index (AIIB, 2005), and A Matrix Tool for Assessing the Performance of Intelligent Buildings (Bssi, 2005), etc. These works propose to measure the building and its systems.

Over 40 per cent of energy is consumed by buildings by their materials manufactured and transported; by construction works on site, and then operating the building. Energy crisis has been a crucial issue, particularly recently. However, none of these IB assessment systems have sufficiently addressed the total energy consumption of IBs or the reaction of the people. To address this issue, Chen et al. (2006) proposed a life span energy efficiency approach using an analytic network process (ANP) model to partly assess the intelligence of a building. The decision model, called IB Assessor, was developed using a set of lifespan performance indicators selected by using an self-invented approach, called energy-time consumption index (ETI), which is the rate of energy consumption. The ETI of a building component is defined as the ratio the sum of embodied energy plus operational energy of the building component over the sum of time required in its manufacturing, constructing and installing and operating. However, it appears that their IB Assessor can be further improved.

- Previous life cycle analysis/assessment (LCA) studies (Shen et al., 2002; Smith, 2000) suggest that the life span of a building consists of at least five successive stages in building design, construction, commission, operation relevant to their structural and services system, and demolition. While claiming that their model was a "lifespan energy efficiency approach", Chen et al. (2006) did not consider energy consumption in building demolition. Their data for embodied energy were estimated figures, because the data were not available.
- In addition, some assumptions about their decision models are not realistic. While selecting indicators for ETI, the model of chen et al. (2006) suggests that a building component with a lower embodied energy is more intelligent than that with a higher one. This is questionable. For example, almost all the building materials consumed in the construction industry in Singapore are imported from overseas, thus are high in terms of embodied energy, as significant amount energy has to be consumed for sea freight. Cement, a basic building material, is mainly from China, Taiwan and Japan (Wu, 2004). It is not convincing to say a building in Singapore is not intelligent simply because it is not constructed in China. The ETI approach of Chen et al. (2006) does not address the impact of energy consumption pattern of building occupants, or

the external environment hence geographical location of a building, for example, humidity, air speed and the temperature, and their impact on the energy consumption rate of a building; although it is widely agreed that these factors can have significant impacts on the rate of energy consumption.

- Another question is whether ANP is the right technique for deducing the weightings for the indicators used in the ETI approach. ANP is one of the multi-criteria decision making (MCDM) techniques. It is usually deployed to derive weightings for a range of variables so they can be compared subjectively (Satty, 1996). However, in the ETI approach, there is only one criterion for indicator selection, that is, energy consumption rates of building components, which is objective data.

Previous IB assessments have been conducted manually, which is time-consuming and can seldom provide feedback to either the occupants or the facilities managers. None of the existing assessment models have clearly addressed the link between energy consumption rate and the response of occupants and business in an IB.

To assess the energy consumption in IBs and to address the problems of the model developed by Chen et al. (2006), this study proposes an alternative sensor based intelligent building assessment model. Following the background, the rest of the paper consists of four sections. Section 2 borrows the statistical explanation of the law of entropy to build a link between energy consumption rate and needs of occupants, which is a key word in the definition of an IB in this study. Section 3 is the Sensor Based Real Time IB Assessment model. Section 4 presents an experiment case study to demonstrate how the model can be applied to solve practical problems, followed by Section 5 which concludes the study. The model developed in this study is only applicable to building operations, but has implications for building designs. Buildings refer to office buildings only.

2 Entropy, energy consumption and the needs of occupants

This section introduces the theory of "entropy" to gain an in-depth understanding about the link between energy consumption and satisfying of the needs of occupants. The concept of entropy, which was originally a thermodynamic construct, has been adapted in other fields of study including information theory, psychodynamics, economics, and evolution. The statistical definition of entropy is generally thought to be the more fundamental definition, as from which all other important properties of entropy can be derived (Vikipedia, 2006). The statistical definition of entropy, originally proposed by Boltzmann in 1877, states that if R denotes the number of states in which each molecule has a specified position and velocity (so called "micro-states") which describe the same given macroscopic state defined by measurable thermodynamic variables like pressure or temperature (so-called "macro-states"), then the entropy of the system (gas) (S) is proportional to the logarithm of R, or:

$$S = k_B \ln R \qquad \ldots \text{Eq. 1}$$

Where k_B is the Boltzmann's constant. Boltzmann's postulate of entropy suggests that entropy is a state function which measures the probability for the occurrence of the state. The Second law of thermodynamics, that is, the law of entropy, states that the evolvement of any adiabatically closed system, also called isolated system, is an entropy increasing process, unless extra energy is received from the external environment. Based on Boltzmann's postulate, the Second Law of thermodynamics is that the ultimate status of any isolated system is the status with the maximum probability.

The statistical explanation is illustrated in Figure 1a, 1b, 1c and 1d, where special symbols are used. A dot * represents a molecule that is free to flow anywhere in a cylinder. One molecule is in Figure 1 a, and 4 molecules are in Figure 1b, 1c, and 1d. p_{right} represents the probability that a molecule stays at the right side of the cylinder, $p_{right} = p$. Let us say, $p = 0.5$. The probability that a molecule stays at the right side of the cylinder is, thus, 0.5. It is important to note that p maybe any figure between 0 to 1. p_{left} represents the probability that a molecule stays at the left side of the cylinder. $p_{left} = 1 - p$. Since $p = 0.5$, the probability that a molecule stays at the left side is also 0.5. W represents the external work needed to push the four molecules to the right side of the cylinder. The cylinder, together with the four molecules, represents an isolated system. When the four free molecules are stored in a cylinder, the probability that all the four free molecules are on the right side of the cylinder is $C_4^4 0.5^4 * 0.5^0 = \frac{1}{16}$= 0.0625, as shown in Figure 1b. Whilst, the probability that the four molecules are evenly distributed in the cylinder is $C_4^2 0.5^2 * 0.5^2 = \frac{6}{16}$= 0.375, as shown in Figure 1c. Thus, the ultimate status of the distribution of the four free molecules in the cylinder should be as shown in Figure 1c, rather than as represented in Figure 1b. This is because Figure 1c assumes the maximum probability. Still, it is possible for all the four molecules to be pushed to the right side of the cylinder if a certain mount of work, W, is received from the external environment of the isolated system. This is shown in Figure 1d. The magnitude of W is related to the kinetic energy, the amount of the molecule (temperature and pressure), and the probability that the molecule to move to the right orientation (p). The effectiveness of W will be largely governed by the magnitude of p, when the kinetic energy, the amount of the molecule are fixed. For example, a greater W has to be consumed when p is reduced from 0.5 to 0.3, as the chance that all the 4 molecules to stay at the right side of the cylinder will drop 87.04 per cent from 0.0625 to 0.0081, provided that p is reduced from 0.5 to 0.3 ($C_4^4 0.3^4 * 0.7^0$=0.0081; (0.0625-0.0081)/0.0625=87.04%).

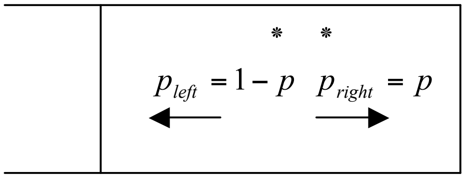

Figure1a
When p=0.5, the probability that a molecule stays at the right side is 1/2.

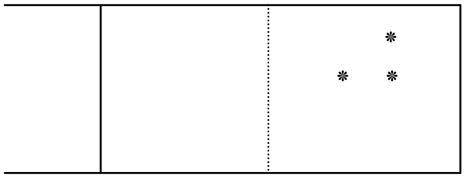

Figure1b
When p=0.5, the probability that all the 4 molecules stay at the right side is 1/16.

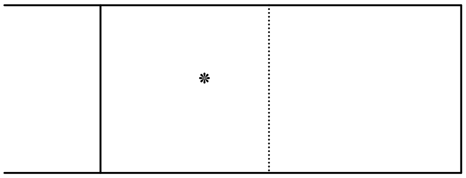

Figure1c
When p=0.5, the probability that 2 of the 4 molecules stay at the right side is 6/16.

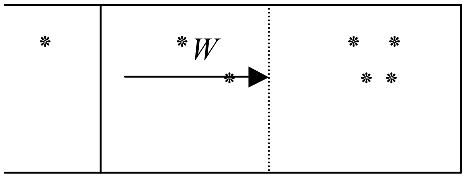

Figure1d
All the 4 molecules are pushed to the right side by W.

Whilst the law of entropy and Figures 1a to 1d are complicated, still three points can be summarized. First, an isolated system will usually involve into a chaos status, unless external energy is received. Second, the achievement of an ordered status is also related to the feature of the system, even external energy can be received. The last but not the least, a system may assume different granularity of order.

By analogy, the cylinder may represent an office building. The right orientation of the cylinder may represent the attainment of satisfaction by its occupants. W may represent the effort, for example, energy consumed by heating, ventilation or air conditioning system to provide a comfortable environment. p is related to the capability of a building to meet the demand of its occupants. It is a feature governed by the thermal insulation performance of a building and the energy consumption behaviour of its occupants. Then, Figure 1c, a chaos status, may represent a building that fails to satisfy the needs of its occupants; and Figure

1d, a special order, may represent the attainment of well-being by its occupants. The effectiveness of W , that is, to boost the building to achieve a comfortable working place, is largely governed by the characteristics of a building.

Obviously, p , which closely related to the intelligence of a building, is the variable which we intend to measure. But, in practice, it is difficult to be calculated with any confidence, as the energy consumption patterns of the building occupants have significantly impact on energy consumption, but can hardly be captured precisely.

The law of entropy and the analogy of an IB to be an isolated system suggest that without the expenditure of energy, it is not possible to create a comfortable working environment. From the analogy, it can be see that it is not appropriate to ignore the response of occupants while assess the intelligence of a building; because an isolated system can assume granularity of order. The analogy also suggests that, p can be measured indirectly through the energy consumed by the building and the degree that the needs of occupants are met. In summary, the extension of entropy to understand the energy consumption, needs of occupants in IBs suggest both energy consumption and the satisfaction level of the occupants are important when assessing the intelligence of the IBs.

3 Sensor Based Real Time IB Assessment (SBR) model

3.1 The model

Maslow's hierarchy of needs is probably the most widely accepted well-being theory relating to needs of occupants in intelligent offices (Clements-Croome, 2004; 2005; 2006). Maslow's hierarchy of needs covered a broad area including factors arranging from physical working conditions, social relationship, and eventually the achievement of creativity and autonomy by the people. CIBSE (2006) suggests that the main factors that influence comfort for people relate broadly to our senses, that is, touch, smell, vision and hearing. Thus an IB must provide a good thermal, aural and visual environment, fresh air, warmth or cooling, no unwanted noise or odours and good light. The design criteria of IBs include the use of space, activity level, clothing level, age of occupants, etc. The focus of the paper is to develop a model to provide real time partial assessment on intelligence of an office building based on its energy consumption. Hence, the Sensor Based Real Time IB Assessment (SBR) model only examines temperature, humidity, lighting, and indoor air quality of the working environment, while recognizing that other factors of the working environment may have an impact on the well-being as well.

The SBR model partially assesses the intelligence of a building by its output, well-being cost index. The model reads 12 variables, which covering illumination quality, thermal quality, air quality and the response of occupants. The well-being cost index is derived from the energy consumption index and indoor climate index. The energy consumption index is derived from indoor air temperature, outdoor air temperature, energy (electricity, fuel and gas) consumption, and energy consumption rates recommended by the building regulations. It measures the effectiveness of the performance of a building. The indoor climate index measures physical working environment and the response of the occupants. Whilst data for energy consumption, temperature, humidity, illumination can be captured by traditional sensors, the feedback of occupants may be captured by sense diary, shown in Figure 3. The sense diary is a touch screen electronic device, originally proposed by Prof. Clements-Croome and will be developed later by the research team. It can record the date, and the satisfactory level of the occupants on temperature, lighting, sound and indoor air quality.

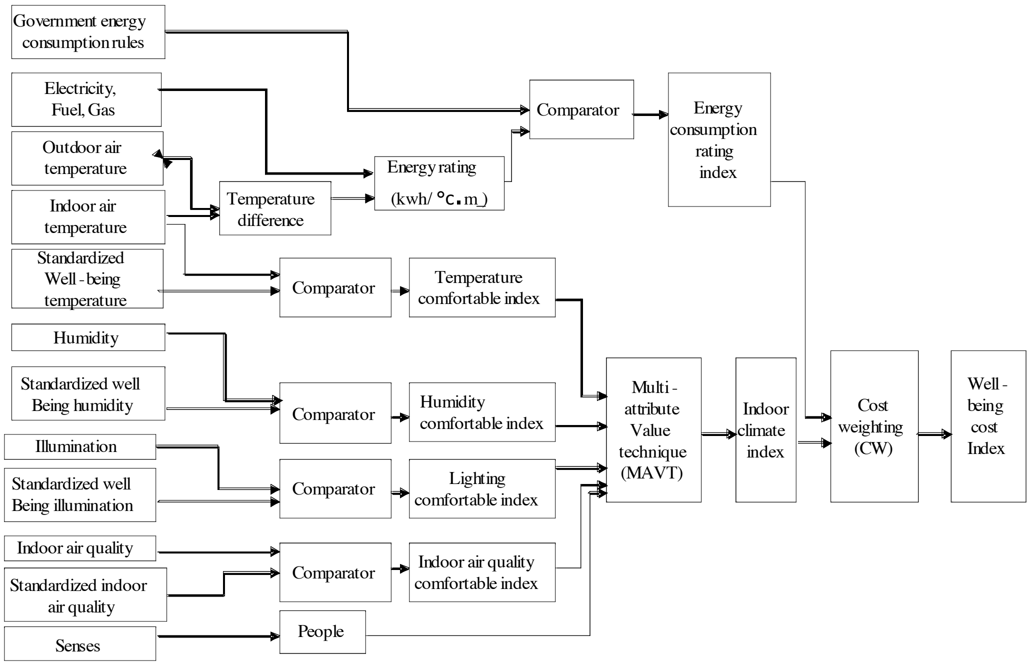

Figure 2 The Sensor Based Real Time IB Assessment(SBR) model

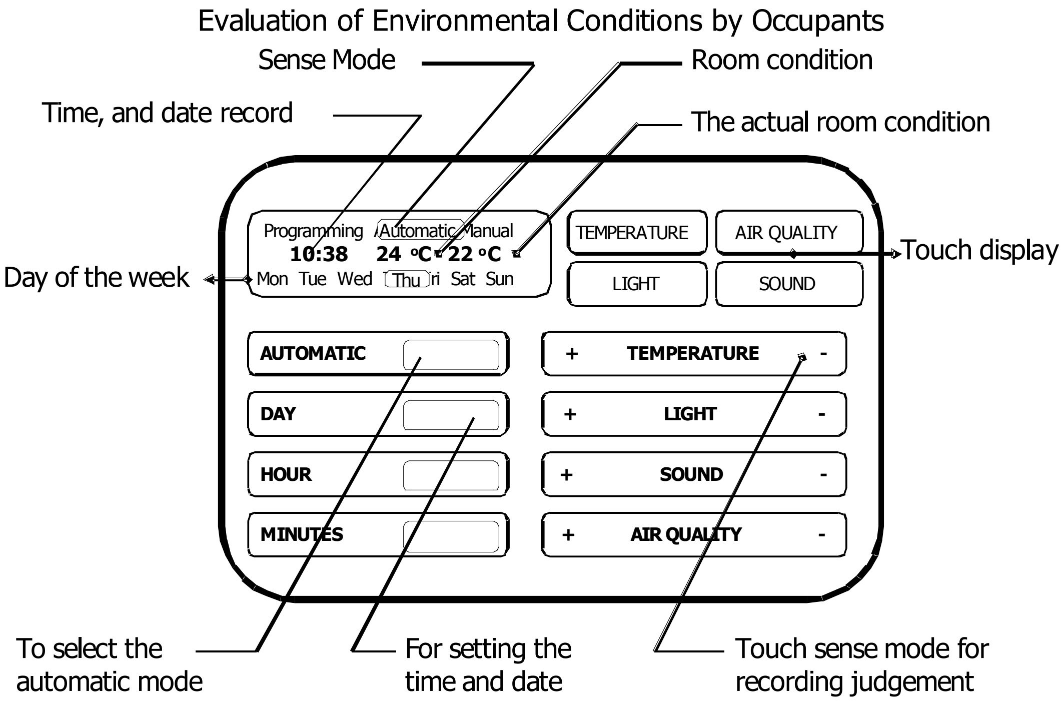

Figure 3 Sense Diary

Figure 2 also illustrates how energy consumption index, temperature comfortable index, humidity comfortable index, lighting comfortable index, indoor air quality comfortable index and indoor climate index can be derived by using the data from sensors. Two key tasks in the SBR model are to drive the cost weighting and the weightings of the sub-factors of the indoor climate index. The process is explained below.

3.2 Cost weighting

The trade-off between for energy consumption rating index and the indoor climate index is a complicate issue. Whilst energy efficiency is a crucial issue in petrochemical, automobile, power plant industries where energy consumption is high; the existing studies suggest that the indoor climate, which linked to productivity, is probably more important than energy efficiency for office buildings (Zsolt, 2005). Woods (1989) and Skaret (1992) suggest that the salaries of workers in typical office buildings exceed the building energy cost by approximately a factor of 100. Hence, even a 1 per cent increase in productivity should be sufficient to cover any expenses related to energy costs (Zsolt, 2005).

Energies in office buildings are mainly consumed by heating, ventilation, air-con, and lighting facilities. Whilst these facilities work together and aim to provide a healthy built environment for the occupants of the buildings; approximately 40 per cent of the existing building stock are sick buildings and are creating sick building syndrome (SBS) for their occupants (Wyon, 1996). The studies of Weinstein (1974), Wyon (1974), Wyon et al., (1979), Boyce et al. (1989), Nunes et al. (1993), Banhidi et al., (1996), Fisk and Rosenfeld (1997) have addressed the relationship between ventilation, temperature, lighting and noise on the performance of workers and suggest that these environment factors can negatively affect the worker productivity. The possible reasons are two counts. First, inadequate ventilation or superfluous emissions from different sources increase the concentration of pollutants, thus reducing air quality. Second, temperature, lighting, noise can affect the well-being of occupants. Reduced air quality and ill-being can negatively affects the central nervous system of the occupants, increasing SBS symptoms such as headache, difficulty in concentration, tiredness. The SBS symptoms can cause distraction from work and productivity loss. This is verified by the field experiments of Baker et al. (1985), Wargocki et al. (1999), Wargocki et al. (2000) and Lagercrantz et al. (2000). The studies of Baker et al. (1985), Raw et al. (1990) and Fisk and Rosenfeld (1997) suggest that a linear relationship exists between SBS and self-estimated productivity. Baker et al. (1985) suggest that the workers presenting with more SBS symptoms were found to respond 7 per cent longer in a continuous performance task and have 30 per cent higher error rate in a symbol-digit substitution test. Fisk and Rosenfeld (1997) estimate that an average decrement in the self-reported productivity of 2 per cent for those occupants with two SBS symptom. Deficient building environment (sick buildings) and SBS symptoms affect not only the worker effectiveness but also their health, giving rise to high social costs. According to the report of US technologies, State and Community programs, poor health and lost productivity associated with office environment alone cost US business more than $438 billion per year (Gassmann and Meixner, 2004).

In the SBR model, the weighting for energy consumption rating index and the indoor climate index is calculated based on the cost of energy, and the cost of productivity loss due to uncomfortable indoor climate. The relationship between dissatisfied indoor climate and productivity loss is presented in Figure 4 (Wyon and Wargocki, 2005). Productivity is linked to salary of employees. Energy consumption is linked to operational costs too. Hence, weightings can be calculated objectively. Traditionally, weightings between comfort and economy criteria are assigned subjectively (Bernard and Kuntze, 2004).

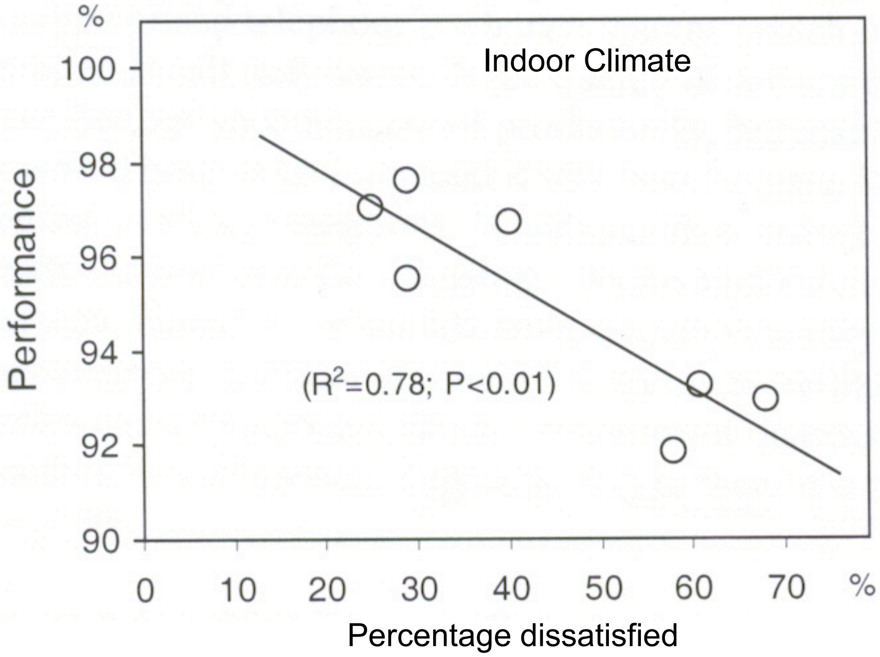

Figure 4 Productivity loss versus dissatisfied indoor climate (Wyon and Wargocki, 2005)

3.3 Weightings of the sub-factors of the indoor climate index

The weightings of the sub-factors of the indoor climate index can be derived by using multi-criteria decision making techniques, for example, multi-attribute value technique (MAVT). The MAVT has been well explained in text books in the field of decision science, thus is not be elaborated here.

3.4 Procedures for implementing the SBR model

To implement the SBR model, five steps may be followed.

1) To identify candidate office buildings;
2) To develop and install the sensor networks including the sense diary in the office buildings;
3) To calculate the cost weightings for the energy consumption index and the indoor climate index;
4) To calculate the weightings for the temperature comfortable index, humidity comfortable index, lighting comfortable index, indoor air quality comfortable index and response of occupants; and
5) To calculate the well-being cost index.

4 An experimental case study

The project is still at its initial stage. The sensor network has not been set up yet, and the sense diary is under construction. Nevertheless, an experimental case study is used to demonstrate how the SBR model can assist in partial assessing the intelligence of a building. Two rooms in the same office building are selected. The cost weighting is calculated based on the study of Wyon and Wargocki (2005). The weighting of temperature comfortable index, humidity comfortable index, lighting comfortable index, indoor air quality index, and response of occupants are derived by survey experts and using MAVT. Sample data of the indexes and their weightings are presented in Table 1. Room A scores higher than Room B. The weightings of the energy consumption index and indoor climate index further suggest that it is not appropriate to ignore the response of occupants when assessing the intelligence of a building, as the weighting of energy consumption index is far less than that of the indoor climate index.

Table 1: Well-being cost index of office Rooms A and B

				Room A	Room B
Energy con. index	Energy		Weighting	0.1	
			Score	90	80
Indoor climate index	Temperature	Temperature comfortable index	Weighting	0.1	
			Score	80	70
		Occupants response	Weighting	0.125	
			Score	70	60
	Humidity	Humidity comfortable index	Weighting	0.1	
			Score	80	70
		Occupants response	Weighting	0.125	
			Score	70	60
	Lighting	Lighting comfortable index	Weighting	0.1	
			Score	80	70
		Occupants response	Weighting	0.125	
			Score	70	60
	Indoor air quality	Indoor air comfortable index	Weighting	0.1	
			Score	80	70
		Occupants response	Weighting	0.125	
			Score	70	60
Well-being cost index				76	66

5 Conclusions

By extending the law of entropy into the area of intelligent building, this paper demonstrate that both energy consumption and the response of occupants are important when partially assessing the intelligence of a building. This study also develops a Sensor Based Real time Building Intelligence assessment (SBR) model. The SBR model can provide feedback to the occupants or the facility manager to monitor the health of the building and to improve the maintenance performance.

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