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A REAL TIME BUILDING ENERGY EFFECTIVENSS 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 facilities manager to improve and maintain their system. After a critical review of the models in a previous published paper regarding building intelligence assessment, this study develops a sensor based real time office building energy effectiveness assessment model. The new model considers both the energy consumption of the building and the responses of its occupants. A case study demonstrates how the model can be implemented. Code is provided as well.

KEYWORDS

Real-time, energy consumption, building, assessment

1. BACKGROUND

In the last two decades, intensive research has been done in the area of intelligent buildings (IBs) [1,2]. One important topic in IB research is building intelligence assessment, as it may lead to methods for evaluating new and existing building designs, and assists the building manager in monitoring the 'health' of the building. There are a number of IB assessment systems available now [3-7]. Over 45 per cent of energy is consumed by buildings which arise from the embodied energy in materials and the operational energy for running its building service systems. Whilst these IB assessment systems assess the building and its systems; none of them has sufficiently addressed the total energy consumption of IBs. To address this issue, a recent study [8] proposed a life span energy efficiency approach using an analytic network process (ANP) model. The decision model, called IB Assessor, was developed using a set of lifespan energy performance indicators selected by using an energy-time consumption index (ETI). However, it seems that the models in [8] need to be improved.

2. A CRITICAL REVIEW OF THE MODELS IN CHEN ET AL. [8]

Previous life cycle analysis/assessment (LCA) studies [9,10] suggest that the life span of a building consists of a number of successive stages in building design, construction, commission, operation relevant to their structural and services system, and demolition. While claiming that they were "lifespan energy efficiency approaches", the models in [8] did not encompass energy consumption in building demolition. Furthermore, their embodied energy consumption rate model, together with their method for the calculation of that embodied energy consumption rate, could be improved significantly.

Their embodied energy consumption rate model

The authors in Chen et al. [8, p.400] defined the embodied energy consumption rate as ETI. The ETI function (F_{ETI}) was proposed as:

$$F_{ETI} = f(e,t) \quad \text{Eq.1}$$

where e was energy, t was time. Their theoretical method to calculate the ETI for an indicator i (ETI_i) was proposed as a partial time derivative of the Eq (1), and was given by:

$$ETI_i = \frac{\partial F_{ETI_i}}{\partial t} \quad \text{Eq.2}$$

Their practical method to calculate the ETI_i was proposed as:

$$ETI_i = \frac{SEC_i}{STC_i} = \frac{SEC_{i,1}+SEC_{i,2}}{STC_{i,1}+STC_{i,2}} \quad \text{Eq.3}$$

where SEC_i was the score of energy consumption of indicator i, STC_i was the score of time consumption of indicator i, $SEC_{i,1}$ was the score of the embodied energy consumption of indicator i, $SEC_{i,2}$ was the score of the operational energy consumption of indicator i, $STC_{i,1}$ was the score of the time consumption of indicator i for its manufacture, transportation, and installation, $STC_{i,2}$ was the score of the time consumption of indicator i for its operation.

Eq. (3) and Eq. (2) suggest that the variable F_{ETI} has the same unit as that of energy. However, Eq. (1) suggests that the variable F_{ETI} is a combination of two variables which are energy and time. Eqs (3) and (2) thus contradict with Eq. (1). It seems that e in Eq. (1) might be energy consumption rate. But, if e is the energy consumption rate, then ETI in Eq. (2) should be e. In addition, Eq. (3) shows that operational energy is included in both F_{ETI} in Eq. (1) and ETI_i in Eq. (2). Operational energy and embodied energy are two distinct concepts. Hence, it is not appropriate for ETI to be called as "embodied energy consumption rate"[8, p.400].

Their practical method for calculating the embodied energy consumption rate

Following the proposal of their so called "practical method for calculating the embodied energy consumption rate", Chen et al. [8] subjectively defined the fundamental scales for score of energy consumption (SEC) and score of time consumption (STC) (see Table 1).

Based on their fundamental scales for energy and time consumption, the researchers provided ETI_i for 43 indicators (see Table 2). To analyze their data, these indicators have been regrouped.

The researchers estimated that the scope of ETI was between 20 and 1000 (see Table 2). They then used Gann's square of nine to select a group of Key performance indicators (KPIs) (see Table 3)

There are a number of inconsistence among Tables 1 to 3 and Eq. (3). Firstly, the fundamental scales of SEC and STC in Table 1 haven't been designed properly. For example, Table 2 shows that the SEC and STC for "construction materials", the 1st indicator are 16 and 9 respectively. However, neither 16 for SEC nor 9 for STC has been defined in Table 1. In addition, for STC, Table 2 also shows that 1+2=3, see "waste disposal", the 21st indicator. Does (0, 1 day) + (1 day, 1 week) = (1 week, 1 month)? To address this problem, a fuzzy approach might be a better solution.

Table 1. Fundamental scales of SEC and STC

Scales for scoring		Product	Process
Score of energy consumption (SEC_i)		$SEC_{i,1}$ Embodied energy of products in manufacture, construction and installation	$SEC_{i,2}$ Energy required in operation processes upon People' occupancy requirement
1=extremely low	6=high		
2=very strongly low	7=moderately high		
3=strongly low	8=strongly high		
4=moderately low	9=very strongly high		
5=low	10=extremely high		
Score of time consumption (STC_i)		$STC_{i,1}$ Time required for product in manufacture, construction and installation	$STC_{i,2}$ Time required in operation processes upon People' occupancy requirement
1=(0,1 day)	4=(1 month, 1 year)		
2=(1day, 1week)	5=>1 year		
3=(1week, 1 month)			

Table 2. Indicators and their ETI_i values

	Indicator	$SEC_{i,1}$	$SEC_{i,2}$	SEC_i	$STC_{i,1}$	$STC_{i,2}$	STC_i	ETI_i
1	Construction materials	8	8	16	4	5	9	178
2	Green materials	5	5	10	3	5	8	125
3	Electricity and electrical services	7	5	12	1	5	6	200
4	Ventilation and air conditioning	6	9	15	3	5	8	188
5	Building services automation system	9	7	16	4	5	9	178
6	IT & C facility and services	8	6	14	3	5	8	175
7	Lifts/escalator and controls	5	8	13	3	5	8	163
8	Lighting	4	3	7	3	5	8	88
9	Conference and meeting facility	1	3	4	3	5	8	50
10	Reserve electric power	7	3	10	3	5	8	125
11	Security and safety control	6	5	11	3	5	8	138
12	Structural monitoring and control	4	4	8	3	5	8	100
13	Fire detection and resistance	4	3	7	4	4	8	88
14	Heating services	7	9	16	3	5	8	200
15	Flushing water system	6	4	10	3	5	8	125
16	Drainage	2	1	3	2	5	7	43
17	External decoration	5	6	11	4	5	9	122
18	Internal decoration	4	4	8	3	5	8	100
19	Lavatory accommodation	4	5	9	3	5	8	113
20	Refuse collection	5	4	9	3	5	8	113
21	Waste disposal	1	2	3	1	2	3	100
22	Potable water system	5	3	8	3	5	8	100

	Indicator	$SEC_{i,1}$	$SEC_{i,2}$	SEC_i	$STC_{i,1}$	$STC_{i,2}$	STC_i	ETI_i
23	Circulation for disabled	5	5	10	4	5	9	111
24	Car park/transportation facility	2	3	5	2	5	7	71
25	Entertainment facilities	1	4	5	2	5	7	71
26	External landscape	2	3	5	2	5	7	71
27	Property management	1	5	6	2	5	7	86
28	Cleanliness	4	3	7	3	5	8	88
29	Building architecture design	4	2	6	4	1	5	120
30	Green design	6	2	8	4	5	9	89
31	Computer aided design	5	2	7	4	5	9	78
32	Computer aided construction/installation	2	8	10	4	5	9	111
33	Computer aided manufacturing	8	1	9	4	5	9	100
34	Means of escape	1	1	2	3	5	8	25
35	Usable areas	1	1	2	2	5	7	29
36	Environmental friendliness	1	2	3	1	5	6	50
37	Extensive use of artificial intelligence	4	2	6	4	5	9	67
38	Existence of green features	1	1	2	1	5	6	33
39	Access sign and directory	1	1	2	1	5	6	33
40	Maintainality	1	1	2	1	5	6	33
41	Flexibility for renovation	4	3	7	2	5	7	100
42	Electromagnetic compatibility	3	1	4	2	5	7	57
43	Thermal comfort and indoor air quality	5	8	13	3	5	8	163

Table 3. Gann's square of nine for KPI identification

	1000	990	980	**970**	960	950	940	930	**920**
660	650	640	630	**620**	610	600	590	**580**	910
670	**380**	370	360	**350**	340	330	**320**	570	900
680	390	**180**	170	**160**	150	**140**	310	560	890
690	400	190	**60**	**50**	**40**	130	300	550	880
700	**410**	**200**	**70**	**20**	**30**	**120**	**290**	**540**	**870**
710	420	210	**80**	**90**	**100**	110	280	530	860
720	430	**220**	230	**240**	250	**260**	270	520	850
730	**440**	450	460	**470**	480	490	**500**	510	840
740	750	760	770	**780**	790	800	810	**820**	830

Second, some of the energy and time consumption score data in Table 2 are questionable. Based on common senses, indicators No. 4-9 (ventilation and air conditioning, building services automation system, IT & C facility and services, lifts/escalator and controls, and lighting) are components of indicator No. 3 (electricity and electrical services). However, Table 2 shows the SEC and STC for indicator No. 3 is even less than those of its components, for example, indicators No. 5 and No.

6. The problem is that some indicators in Table 2, which include but not limited to indicators No. 3-9, are not in the same level in the hierarchy in terms of energy consumption, but are put in the same level. Besides, embodied energy is the energy consumed by the procedures associated with the mining, production, delivery, and construction of building materials and building components. Maintainality, flexibility for renovation, electromagnetic compatibility, and thermal comfort and indoor air quality (indicators No. 40-43) are neither building materials nor building components, thus do not carry embodied energy, $SEC_{i,1}$ or $STC_{i,1}$.

The last but not the least, according to Eq. (3), all the numbers in the last column in Table 2 are incorrect, as they are overstated by 100 times. For example, the ETI value for "construction materials", the 1st indicator in Table 2 should be 1.78, rather than 178. For this reason, the relevance of the Gann's square of nine in Table 3 with the purpose of identifying their KPI requires more study, as all the ETI in Table 2 should be in the scope of 0.25 to 2.00, while the numbers in Table 3 are in the scope of 20 to 1000.

Their ANP method

The researchers used the analytical network process (ANP) method to derive the weighting for factors selected from Tables 2 & 3. ANP is one of the many multi-criteria decision making (MCDM) techniques. It is usually deployed to derive weightings for a range of variables when multiple criteria have to be considered, so variables with different units can be compared subjectively [11]. In the ETI approach, there is only one (not several) criterion for indicator selection, that is, energy consumption rates of building materials/ components. Energy consumption rate of any building materials/ components can be expressed in terms of J/S or W. Hence, ANP is not relevant at all.

Their assumptions

The ETI approach in [8] did not address the impact of energy consumption patterns of the building occupants, or the impact of the geographical location of a building on its energy consumption rate. In addition, the ETI based indicator selection process in [8] suggested that a building component with a lower embodied energy was more intelligent than that with a higher one, which is questionable too, as transportation cost energy, and it has little to do with "building intelligence". 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 [12]. It is not convincing to say a building in Singapore is not intelligent simply because it is not constructed in China.

3. SENSOR BASED REAL TIME IB ASSESSMENT (SBR) MODEL

The model

As suggested earlier, the model of Chen et al. [8] did not cover the entire life span of a building. Indeed, it is very hard, if not possible, to collect embodied energy data for a particular building. Besides, the existing IB assessment can only be done manually, and seldom consider the responses of occupants. CIBSE [13] 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 should at least provide a good thermal environment, fresh air and good light. Hence, the aim of this paper is to develop a sensor based real time office building energy effectiveness assessment model. The model focuses on the building operation stage, and examines the energy effectiveness by considering energy consumption of a building and comfort of its occupants. The model is presented in Figure 1.

The model assesses the energy performance of a building by a well-being cost index. It reads nine variables, which covering thermal quality, illumination 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

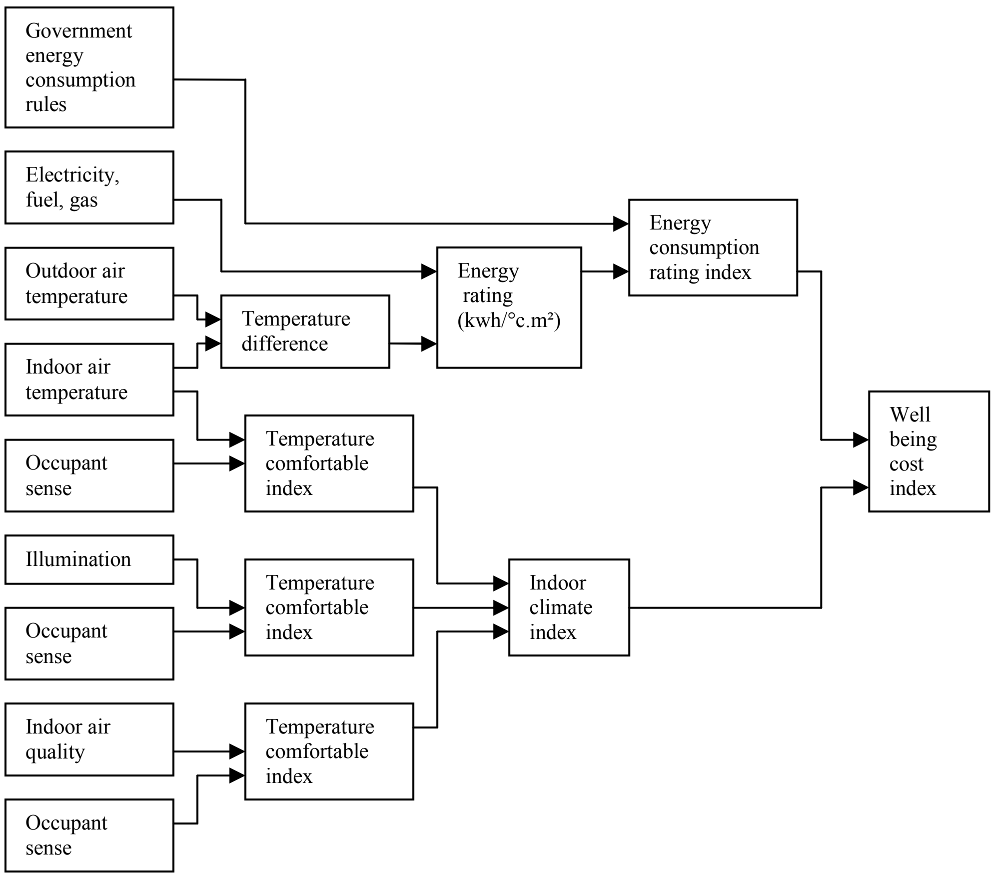

Figure 1. Real time building intelligence assessment model

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 2. The sense diary is a touch screen electronic device [14]. It can record the date, and the satisfactory level of the occupants on temperature, lighting, sound and indoor air quality.

Figure 1 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 model are to drive the cost weighting and the weightings of the sub-factors of the indoor climate index. The are explained hereunder.

Cost weighting

Energies in office buildings are mainly consumed by heating, ventilation, air-con, lighting facilities. These facilities work together and aim to provide a health built environment for the occupants of the buildings. It is estimated that approximately 40 per cent of the existing building stock are sick buildings and are creating sick building syndrome (SBS) for their occupants [15]. The studies of Weinstein [16], Wyon [17], Wyon et al.[18], Boyce et al. [19], Nunes et al.[20], Banhidi et al.[21], Fisk and Rosenfeld [22] 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. Because inadequate ventilation or superfluous emissions from different sources increase the concentration of pollutants, thus reducing air quality. In addition, 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 [25-26].

Baker et al.[23] and Fisk and Rosenfeld [22] suggest that a linear relationship exists between SBS and self-estimated productivity. Baker et al. [23] 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 [22] 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 [1].

The trade-off between energy consumption rating index and the indoor climate index is thus a complicate issue. Whilst energy efficiency is a crucial issue in petrochemical, automobile, power plant industries where energy consumption is high; the indoor climate, which linked to productivity, is probably more important than energy efficiency for office buildings [27], as the salaries of workers in typical office buildings exceed the building energy by approximately a factor of 100 [28-29]. Hence, even a 1 per cent increase in productivity should be sufficient to cover any expenses related to energy costs [27].

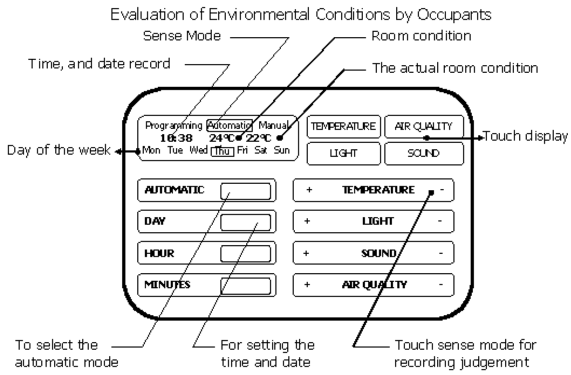

Figure 2. Sense diary [14]

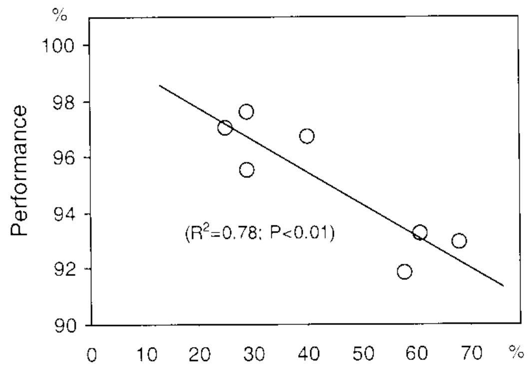

Figure 3. Productivity loss versus dissatisfied indoor climate [30]

In our 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 3 [30]. Productivity is linked to salary of employees. Energy consumption is linked to operational costs. Hence, weightings is calculated objectively. Traditionally, weightings between comfort and economy criteria are assigned subjectively [31].

Weightings 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.

Procedures

To implement the model, five steps may be followed:

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

An experimental case study

The project, with its web site at www.cmips.org.uk/members.htm, has four partners. The industry partners are responsible for setting up the sensor networks and data visualization. The authors are responsible for developing the building energy effectiveness assessment models. Field data are not available at this stage. Hence, an experimental case study is provided for the industry partners to demonstrate how the model can be deployed to assess the energy effectiveness 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 [30]. The weighting of temperature comfortable index, humidity comfortable index, lighting comfortable index, and indoor air quality index are derived by survey experts and using MAVT. Sample data of the indexes and their weightings are presented in Table 4. 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 energy effectiveness of a building, as the weighting of energy consumption index is far less than that of the indoor climate index, which related to occupants responses.

Table 4. 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 comfortable index	Weighting	0.3	
		Score	80	70
	Humidity comfortable index	Weighting	0.2	
		Score	80	70
	Lighting comfortable index	Weighting	0.2	
		Score	80	70
	Indoor air comfortable index	Weighting	0.2	
		Score	80	70
Well-being cost index			81	71

4. CONCLUSIONS

The existing building intelligence assessment models seldom consider the responses of the occupants in the building. Besides, these models can only be conducted manually, thus can hardly provide timely assistance for facilities manager to improve and maintain their facilities. After a critical review of the models in a previous published paper regarding building energy intelligence assessment, this study develops a sensor based real time office building energy effectiveness assessment model. The new model considers both the building energy consumption and the responses of its occupants, and can provide feedback to the occupants or the facility manager to monitor the energy effectiveness of the building, thus improving the maintenance performance. A case study demonstrates how the model can be applied in real life.

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THE COMPUTER CODES

The codes, written in Java, are for computing the well being cost index.

```
/*
   Compute the overall index at a point with
formatting
   using standard input and output
   Author: Min Wu
   File: PointAssessment.java
*/
import java.util.*;
import java.text.*;
class PointAssessment {
public static void main( String[] args ) {
double T, Tindex, L, Lindex, RH, Hindex, Pindex;
 Scanner scanner;
 DecimalFormat df = new DecimalFormat("0.00");
 scanner = new Scanner(System.in);
  //Get input
 System.out.print("Enter T: ");
  T = scanner.nextDouble();
  System.out.print("Enter L: ");
  L = scanner.nextDouble();
  System.out.print("Enter RH: ");
  RH = scanner.nextDouble();
  //Compute temperature index
  if ((T<0) || (T>36))
  { Tindex=0.0; }
  else
  { if(T<16)
  {Tindex=(15.0/4.0)*T;}
   else
  {if(T<20)
  {Tindex=10.0*(T-16)+60.0;}
   Else
   {if(T<24)
    {Tindex=100.0;}
   else
   {if(T<30)
   {Tindex=(-20.0/3.0)*T+260.0;}
    else
    {Tindex=-10.0*T+360.0; } } }}
    //Compute lighting index
    if ((L<0.0) || (L>2500.0))
     {Lindex=0.0;}
     else
     {if(L<500.0)
     {Lindex=0.2*L; }
      else
      {if(L<2000.0)
{Lindex=100.0;}
Else
{Lindex=(-0.2)*L+500.0;}} }
 //Compute humidity index
if ((RH<0.0) || (RH>1.0))
{Hindex=0.0; }
else
{if (RH<0.3)
{Hindex=(1000.0/3.0)*RH; }
```

```
 else
 {if(RH<0.7)
 {Hindex=100;}
 else
{Hindex=(-1000.0/3.0)*RH+(1000/3.0);}}}
Pindex=(1.0/3.0)*Tindex+(1.0/3.0)*Lindex+(1.0/3.0
)*Hindex;
 //Display the results
 System.out.println("");
 System.out.println("Given T: " + T);
 System.out.println("Tindex: " + df.format(Tindex));
 System.out.println("");
 System.out.println("Given L: " + L);
 System.out.println("Hindex: " + df.format(Lindex));
 System.out.println("");
 System.out.println("Given RH: " + RH);
 System.out.println("Hindex: " +
df.format(Hindex));
 System.out.println("");
 System.out.println("Pindex: " + df.format(Pindex));
}}
```