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An OTTV-based energy estimation model for commercial buildings in Thailand

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Abstract

The use of OTTV as a measure of average heat gain across the building envelope of an air-conditioned commercial building has been accepted since it was introduced into Thailand and other ASEAN countries. Other studies have concluded that the average zone cooling coil load of an air-conditioning system can be taken to comprise the sum of the average external load, internal loads, and terms representing the storage effects of the exterior wall and internal masses of the building components in that zone. This conceptual relationship is used as the basis for postulating an equation that linearly relates the cooling coil load of a building zone over a period to its external factor represented by the OTTV and its internal factors represented by all internal loads over the same period. It is also used to postulate an equation that relates the energy use by the building to the cooling coil load and the direct loads. This study utilizes DOE-2 simulation program in a series of parametric runs to develop an OTTV formulation each for four types of commercial buildings. The resulting OTTV formulations were used in further parametric runs to develop a formulation each for the cooling coil load and for energy use in the form postulated. The formulations are validated using field audit results.

Keywords: Energy prediction; Overall thermal transfer value; Building energy simulation; Parametric simulation; Building cooling load

1. Introduction

Predicting energy use in buildings has long been a subject of interest for many groups of professionals. Degree-hour and degree-day have been used as measures of heating and cooling requirements for residential and small commercial buildings with certain degree of acceptance. These indicators have been based on steady or static heat flow concept and were initially applied successfully to predict heating energy required for single houses or small buildings with single zone and simple schedule [1–3]. These were extended with introduction of variable base temperature and solar utilizability factor and applied also to predict cooling energy use [4–6]. When detailed weather data are available and are classified into different ranges of values for different periods of each day, the bin method of ASHRAE [7], considers usage pattern of a house and different performance regimes of heating and cooling equipment under different temperature ranges. This method offers a high potential for accuracy, but still is suitable for simple buildings.

For large commercial buildings comprising multiple number of zones, static methods do not apply well and computer simulation programs have been used successfully to predict heating or cooling requirements and energy use over a given period [8–11].

A number of countries in the world have adopted mandatory requirements on energy conservation for buildings [12]. The Philippines, Singapore, and Thailand require that the overall thermal transfer value-OTTV of a commercial building must not exceed a statutory limit [13]. The OTTV is formulated from a fundamental consideration of heat gain across the envelope of a given building and has been used as a measure of average rate of heat gain across the envelope into the interior of an air-conditioned space. It accounts for the construction (composition of glazing and other opaque members of the envelope including sun-shading devices), types of materials used, orientation, types of building (office, hotel, etc.). It also accounts for weather-related influences such as the effect of solar radiation and ambient temperature of the location.

Interests exist among the regulatory officials, professional, and academics in these countries to relate OTTV of a building to cooling requirement and energy use of the building. Ref. [14] presents a simple formulation for predicting energy use of commercial buildings in Singapore based on results of simulations of a model of commercial building using DOE-2 program. Ref. [15] presents a simple expression re-

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lating annual air-conditioning energy use of a building to its OTTV and cooling-degree days of Singapore. The authors in [15] later extended the concept to predict peak cooling load of a building [16].

In Thailand, the Energy Conservation Promotion Act (ECP Act) of 1992 requires that the management of every large commercial buildings conduct energy audit and set up plans to improve energy efficiency. Consultants routinely compile information on building shape and construction, and other details such as lighting power density, equipment power density and schedule of use of each space. Measurements are taken so that the performance of the air-conditioning system can be evaluated. Calculated value of OTTV of each façade and of the building is given in each energy audit report [17]. A question inevitably ensues during the conduct of the energy audit is how energy use in a building is related to the energy performance parameters (such as OTTV and the performance of the air-conditioning system) and energy usage parameters (such as lighting power density) of the building.

This paper will first show conceptually that the cooling load sensed by the cooling coil in an air-conditioned zone is the sum of an exterior-driven heat gain term and other terms representing heat generated by interior sources. A well-known simulation program called DOE-2, version 2.1 E, is then used in a series of parametric runs to give monthly OTTV formulations for a generic building. The parametric results show that monthly cooling requirements of the generic buildings are linearly related to OTTV, power density of lighting, equipment and other contributing components in a space. The monthly energy use is calculable from the derived cooling requirements when the coefficients of performance of the air-conditioning system are given. The results are applied to data obtained from energy audits of a number of commercial buildings. The results of the application show that monthly and annual energy uses predicted by the formulation agree well with metered energy use.

A revision of the energy conservation requirements is under way in Thailand. It has been proposed that apart from requiring that the lighting system, air-conditioning system and building envelope of a building to individually comply to a minimum efficiency level, an alternative path of whole building energy compliance be introduced as a part of the new revised by-laws and regulations. The energy estimation model to be described in this paper would be employed for the purpose of evaluation of compliance of a given building.

2. Dynamics of cooling requirement and energy use in buildings

The mechanisms of heat flow into an air-conditioned zone and the contribution to the cooling load as sensed by the cooling coil of the air handling system in the zone can be illustrated by the room in Fig. 1. The load to the cooling coil, which is also called the cooling coil load, is transferred to it

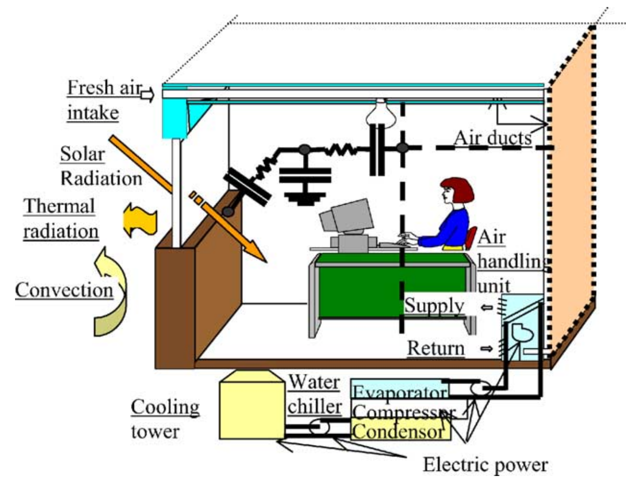

Fig. 1. An air-conditioned room in a building and the representation of the storage effects of wall, air, and other interior members each by a capacitor.

from the moist air in the space. Such load comprises a sensible component and a latent component and is contributed to it by heat convected from all surfaces in the room and moisture added to the air from various sources in the room. Our objective is to show that the cumulative cooling coil load over a given period of time or its average value over a period can be considered to be contributed from various sources independently in an additive way.

For the purpose of the present study, the room illustrated in Fig. 1 is an adequate model for study of heat flow and thermal storage. This room is assumed to be one of many in a multi-storeyed building. An exterior wall comprises an opaque section and a transparent window and faces external environment. The interior is air-conditioned. The sidewalls of this room connect this room to similar adjacent rooms. The internal wall opposite the window connects this room to another zone which is un-conditioned. Ref. [18] uses a similarly structured room model for their study of storage loads in an air-conditioned room.

2.1. Dynamic heat gain and cooling coil load

Heat gain or loss between exterior surrounding and a space separated by a building envelope takes the form of conduction transfer through the opaque part of the envelope, radiation, and conduction transfer through the transparent fenestration and exchange of air through ventilation and air leakage.

2.1.1. Opaque walls

At the surfaces of an opaque wall, solar and thermal radiation together with convection heat transfer causes a net conduction heat flow into the wall material. Within the wall, conduction heat transfer is governed by the heat diffusion equation. Studies, [19,20], have shown that the heat transfer mechanism is represented by a set of linear dynamic equations.

2.1.2. Transparent fenestration

The dynamics of heat transfer is much faster than that at the opaque wall because the transparent members are much thinner and lighter. However, direct solar radiation is also transmitted across a fenestration in this case.

2.1.3. Ventilation and air leakage

Direct exchange of air between the exterior and interior of the space brings load directly to the cooling coil of the air-conditioning system serving the space.

2.1.4. Dynamic change of air enthalpy and cooling coil load

Because of the mass of the air in the space is finite, incremental change of the air enthalpy due to heat convected to it from surfaces in the space, moisture evaporated into it and the incremental removal of heat by the cooling coil occurs in a balance condition over an incremental time. The process of change of air enthalpy in the interior space is also dynamic. The equation relating change of the enthalpy of the air can be written in the form:

$$\begin{aligned} M\frac{\mathrm{d}h_i}{\mathrm{d}t} = {} & \sum_j h_{\mathrm{c}ij}A_j(T_{\mathrm{w}ij} - T_i) + \dot{m}_{\mathrm{v}}(h_{\mathrm{ao}} - h_i) \\ & + \dot{m}_{\mathrm{f}}(h_{\mathrm{ao}} - h_i) \\ & + \text{sensible heat convected from human occupants} \\ & + \text{latent heat from human occupants and other} \\ & \quad \text{sources} + \dot{m}_{\mathrm{s}}(h_{\mathrm{s}} - h_i) \end{aligned} \tag{1}$$

where A_j is the area of surface j in heat convection exchange with air (m^2), h_{ao} the enthalpy of ambient air at the exterior of the building (kJ kg^{-1}), h_i the enthalpy of air in the exterior space (kJ kg^{-1}), h_{s} the enthalpy of air after passage through the cooling coil (kJ kg^{-1}), $h_{\mathrm{c}ij}$ the coefficient of convection heat transfer from surface j in the interior space, M the total mass of air in the space (kg), $\dot{m}_{\mathrm{f}}$ the mass flow rate of leakage air (kg s^{-1}), $\dot{m}_{\mathrm{s}}$ the mass flow rate of supply air from the cooling coil (kg s^{-1}), and $\dot{m}_{\mathrm{v}}$ is the mass flow rate of ventilation air (kg s^{-1}).

Also, $M(\mathrm{d}h_i/\mathrm{d}t) = \sum_j h_{\mathrm{c}ij}A_j(T_{\mathrm{w}ij} - T_i)$ is the heat conducted from exterior surfaces, $\dot{m}_{\mathrm{v}}(h_{\mathrm{ao}} - h_i)$ the load due to ventilation, $\dot{m}_{\mathrm{f}}(h_{\mathrm{ao}} - h_i)$ the load due to air leakage, and $\dot{m}_{\mathrm{s}}(h_{\mathrm{s}} - h_i)$ is the load due to cooling air.

The above describes the process of heat gain across building envelope into the interior space as a dynamic process represented by linear dynamic equations with external environmental variables (solar radiation, air temperature, etc.) as driving forces. To the first degree, even thermal radiation exchanges between surfaces under limited temperature differences could also be represented by linear relationships. The overall relationship between the cooling coil load and the driving forces can be summarized as follows:

$$\begin{aligned} & \text{Cooling coil load} \\ & = \text{dynamic (and to the first degree linear) loads of heat} \\ & \quad \text{gain across building envelope} \\ & \quad \text{(or load due to external factor)} \\ & \quad + \text{heat gain due to internal factors (such as lighting,} \\ & \quad \text{equipment and human occupants)} \\ & \quad + \text{load of ventilation and air leakage} \end{aligned} \tag{2}$$

In this paper, we will deal with average cooing coil load over a period. The period can be a year or a month. We call this the *cooling requirement* (CR), of an air-conditioned building.

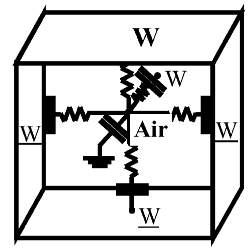

Fig. 2. A thermal model where each wall is represented by a thermal capacitance and each capacitance is connected to the air node.

2.2. Thermal storage and its effect

The effect of thermal storage of building components and systems on cooling energy can be illustrated from a consideration of the following situation for the room in Fig. 1. Suppose the room is used during 13:00–17:00 h on a given day. During the morning hours when the room is not used and air-conditioning is off, there is heat gain into the room from solar radiation and external thermal environment which raise the air temperature in the room far beyond the set-point temperature (25 °C) used during 13:00–17:00 h. Heat is stored in the walls, floors, and other masses in the room including furniture. At 13:00 h the air-conditioning system is turned on. The heat stored in the air, walls, floors and other masses in the room present additional load to the air-conditioning system. This heat must be removed and is in addition to the instantaneous heat gain due to the driving forces prevalent at 13:00 h. However, by 17:00 h the air-conditioning system is turned off and the room is left to accumulate heat gain.

The size of heat accumulated depends on many parameters. The prominent parameters are the heat capacity of the structure, schedule of use of space (and air-conditioning), and ambient conditions [18].

Ref. [21] demonstrates through the use of regression that the thermal response of a wall in a complex structure of a building can be emulated sufficiently accurately by the response of a single thermal capacitance. Fig. 2 illustrates the concept.

Each wall is represented by an effective thermal capacitor, the capacitance value of which is not necessarily equal to the product of its mass and its thermal capacity. Lebrun and Nusgens [22] offer similar analysis methodology for the effects of building thermal storage load.

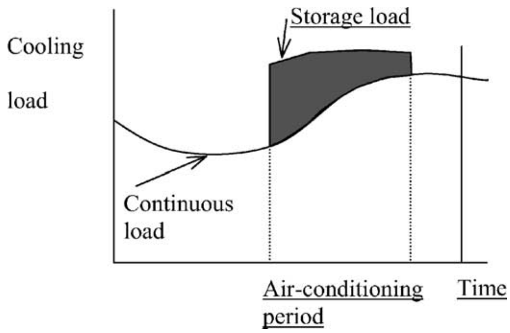

Fig. 3. Illustration of the effect of storage load superimposing on the normal load.

From our model in Eq. (1), it is apparent that the air itself possesses a thermal capacitance and its model capacitor is connected via conducting paths to wall capacitors. Because the exterior wall is directly exposed to solar energy and external environment, it can be fully represented by a thermal capacitor. All interior walls are indirectly coupled to the effects of the external driving forces. To simplify the situation, all interior walls may also be represented by a single thermal capacitor. The simplified model of lumped thermal capacitor for interior walls is shown in Fig. 1.

During the time when air-conditioning is off, heat gain on the external wall and into the room is analogous to current flow into the lumped capacitors in Fig. 1. The charges stored in the capacitors during this period represent heat stored in the walls, floors and other masses. When the air-conditioning is turned on, the stored charges flow as current to the air node and add to the thermal current contributed from the dynamic systems of the walls and other masses driven by the forces of solar radiation and external environment. Fig. 3 illustrates conceptually the additional cooling load from the thermal storage that imposes on the normal load. The cumulative storage load over a period will appear in the cumulative cooling coil load in Eq. (2).

We conclude our argument in this section by summarizing the results in two equations as follows:

$$\begin{aligned}&\text{Cooling coil load over a period or cooling requirement (CR)}\\&\quad= \text{external factors of heat gain through building envelope}\\&\qquad+\text{thermal storage load of envelope}\\&\qquad+\text{internal factors (lighting, equipment, occupants}\\&\qquad\quad\text{ventilation and air leakage or infiltration)}\\&\qquad+\text{thermal storage of the finite masses of walls, floors,}\\&\qquad\quad\text{and furniture (internal mass)}\quad\text{and}\end{aligned}$$

$$\begin{aligned}&\text{Energy use during a period}\\&\quad=\frac{\begin{array}{c}\text{Cooling requirement (CR)}\\\text{during the period}\end{array}}{\text{COP}}\\&\qquad+\text{direct energy use of lighting and equipment}\qquad(3)\end{aligned}$$

where COP is the coefficient of performance of the air-conditioning system and its plant.

3. A generic building model for parametric study

A generic building model will be used in this study. The DOE-2 computer program will be used to calculate the cooling requirement of the generic model for various configurations of the model in order to find appropriate parameter values of OTTV, cooling requirement and energy use based on the simple Eqs. (2) and (3) postulated.

A square building shown in Fig. 4 is used. The building comprises 12 storeys and possesses the dimensions as shown in the figure and in Table 1. The composition of each façade is identical to the others. The values of physical parameters shown in Table 1 are to be used as base-case values but most will be varied during the parametric study.

The building model comprises two zones: peripheral and core zones. The peripheral zone is air-conditioned while the core zone is un-conditioned for each floor. There is no human occupation nor lighting and equipment in the core zone. In this study, we are interested only on the heat gain through wall and the corresponding OTTV formulation for wall. Heat gain through roof is minimized by assigning very low absorptance value for roof surface and specifying heavy insulation for roof. The cooling requirement report from DOE-2 program does not distinguish between that due to heat gain through roof and that due to wall.

The same building model will be used to represent four types of commercial buildings. These are office, hotel, hospital, and department store. The four types of building will be differentiated by three schedules of building use. The three schedules also appear in Table 1.

In the following parametric runs, the cumulative cooling coil load over a month or over a year is obtained for each building schedule. To obtain cooling requirement or average cooling coil load over a period, the cumulative load is divided by *the total number of hours of use of the building over the period*. To obtain CR per unit floor area, the resultant CR is divided by the total air-conditioned area of the building.

Hour by hour weather data of Bangkok for the year 1996 was coded for DOE-2 run. The weather data includes tem-

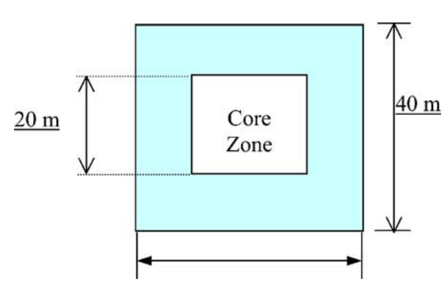

Fig. 4. A generic building model.

Table 1
Details of the generic building model

Item	Values
Number of stories	12
Total area of opaque walls (m^2)	4.053
Total area of glazings (m^2)	3.184
Total area of roof (m^2)	1.421
Total area of floors (m^2)	14.172
Ratio of wall area to floor area	0.51
Ratio of window area to wall area, WWR	0.44
Shading coefficient of glazing, SC	0.64
Overall coefficient of heat transfer for wall, U_w ($Wm^{-2} K^{-1}$)	2.957
Overall coefficient of heat transfer for roof, U_r ($Wm^{-2} K^{-1}$)	0.676
Solar absorptance of wall surface, α_w	0.5
Solar absorptance of roof surface, α_r	0.005
Annual average OTTV (Wm^{-2})	80.41
Air handling system	CAV[a]
Lighting power density,(Wm^{-2})	13.18
Equipment power density (Wm^{-2})	12.88
Interior temperature, T_i (°C)	25
Number of occupants[b] per 100 m^2	7
Number of zones in DOE-2 simulation	2
Zone 1	Floor 1–12
Zone 2	Core
Schedules	
(1) Office 5 days per week (h)	8.00–17.00
(2) Hotel and hospital 7 days per week (h)	0.00–24.00
(3) Department store 7 days a week (h)	10.00–21.00

[a] CAV stands for constant air volume system.
[b] Sensible and latent heat gains per occupant used are 73 and 59 W, respectively.

perature, dry-bulb and wet-bulb, direct and global solar radiation, wind speed and its direction.

4. Parametric runs for the OTTV equation

The OTTV formulation used here is given as:

$$\mathrm{OTTV} = (1 - \mathrm{WWR})(\mathrm{TD_{eq}})(U_w) + (\mathrm{WWR})(\mathrm{SF})(\mathrm{SC}) + (\mathrm{WWR})(\mathrm{DT})(U_f) \quad (4)$$

where WWR is the ratio of window area to total wall area, SF the solar factor, SC the shading coefficient of glazing, DT the average temperature difference between outdoor and indoor, U_f is overall coefficient of heat transfer for glazing, TD_{eq} the equivalent temperature difference across opaque wall accounting for the dynamic-storage effect of the wall mass, and U_w is the overall coefficient of heat transfer for wall.

The first term represents heat gain through opaque wall section, accounting both for thermal conduction due to temperature difference between the exterior and interior of the building and absorbed solar radiation on the wall mass. The second term represents solar gain through transparent window accounting for direct solar transmission and thermal gain from absorbed solar radiation in the glazing. The last term represents thermal conduction gain across the glazing.

Table 2
Ranges of values of three parameters

Parameters	Range of values
OTTV formulation	
U_w (Wm^{-2} floor)	1.054–3.429
U_f (Wm^{-2} floor)	4.369–6.143
SC	0.4–0.8

In a parametric run, the required monthly or annual CR is obtained in each run for a given set of parameter values of the building model. The result forms a pair of the value of a given parameter and the value of CR. The value of the parameter is then varied and another run is taken to give another pair. This process continues until there is a sufficient number of paired values for regression to obtain the requisite value of a target parameter.

In the parametric run for the OTTV, the properties of opaque wall (conductivity, density, and width), glazing (conductivity, width, and shading coefficient), and window to wall ratio were varied sequentially. Table 2 shows the ranges of values of these physical parameters of the building used. The target parameters are TD_{eq}, DT, and SF. In these parametric runs, internal loads were kept unchanged so that the resulting CR varied with external factor term only.

The results of parametric runs and the ensuing regression for OTTV formulation produced results shown in Tables 3–5. The regression results exhibit good linearity between the CR and the parameters. The value of the correlation coefficient in each case exceeds 0.99.

The TD_{eq}, DT, and SF values for a building operated 24 h are lower than those values in other buildings. This is due to the fact that heat gain into these buildings is much lower at night. When average over the period of working hours, heat gains in these buildings are lower than those in other buildings, resulting in the lower TD_{eq}, DT, and SF values.

The TD_{eq} value accounts for the solar absorptance of wall surface as well as the mass of wall. By varying the solar absorptance in each set of parametric runs to obtain a value of TD_{eq}, a set of TD_{eq} values corresponding to different values of solar absorptance of wall surface were obtained The effect of mass of opaque wall on the value of TD_{eq} was also examined through similar parametric runs. Fig. 5 illustrates the effect of solar absorptance and mass of opaque wall on the TD_{eq} value. The TD_{eq} value is more sensitive to solar absorptance than the wall mass.

5. Parametric runs for the CR equation

The relationship between CR, OTTV, other energy usage parameters and the storage load of the interior wall mass is postulated as per Eq. (2) to take the form:

$$\mathrm{CR} = (\mathrm{OTTV}) + C_1(\mathrm{LPD}) + C_2(\mathrm{EPD}) + C_3(\mathrm{VENT}) + C_4(\mathrm{OCCU}) + \mathrm{Storage} \quad (5)$$

Table 3
Regressed relationships for OTTV for schedule 1: office

Month	Relationships
January	OTTV = $13.06(U_w)(1 - \text{WWR}) + 3.98(U_f)(\text{WWR}) + 181.33(\text{SC})(\text{WWR})$
February	OTTV = $12.79(U_w)(1 - \text{WWR}) + 3.95(U_f)(\text{WWR}) + 175.84(\text{SC})(\text{WWR})$
March	OTTV = $14.44(U_w)(1 - \text{WWR}) + 5.00(U_f)(\text{WWR}) + 179.75(\text{SC})(\text{WWR})$
April	OTTV = $14.58(U_w)(1 - \text{WWR}) + 5.24(U_f)(\text{WWR}) + 176.88(\text{SC})(\text{WWR})$
May	OTTV = $13.93(U_w)(1 - \text{WWR}) + 4.65(U_f)(\text{WWR}) + 173.14(\text{SC})(\text{WWR})$
June	OTTV = $13.82(U_w)(1 - \text{WWR}) + 4.65(U_f)(\text{WWR}) + 172.41(\text{SC})(\text{WWR})$
July	OTTV = $13.34(U_w)(1 - \text{WWR}) + 4.45(U_f)(\text{WWR}) + 168.92(\text{SC})(\text{WWR})$
August	OTTV = $12.91(U_w)(1 - \text{WWR}) + 4.48(U_f)(\text{WWR}) + 161.03(\text{SC})(\text{WWR})$
September	OTTV = $12.85(U_w)(1 - \text{WWR}) + 4.41(U_f)(\text{WWR}) + 160.20(\text{SC})(\text{WWR})$
October	OTTV = $13.46(U_w)(1 - \text{WWR}) + 4.57(U_f)(\text{WWR}) + 168.33(\text{SC})(\text{WWR})$
November	OTTV = $13.48(U_w)(1 - \text{WWR}) + 4.35(U_f)(\text{WWR}) + 177.00(\text{SC})(\text{WWR})$
December	OTTV = $12.70(U_w)(1 - \text{WWR}) + 3.79(U_f)(\text{WWR}) + 181.52(\text{SC})(\text{WWR})$
Annual	OTTV = $13.46(U_w)(1 - \text{WWR}) + 4.47(U_f)(\text{WWR}) + 172.99(\text{SC})(\text{WWR})$

Table 4
Regressed relationships for for schedule 2: hotel and hospital

Month	Relationships
January	OTTV = $10.73(U_w)(1 - \text{WWR}) + 3.89(U_f)(\text{WWR}) + 120.61(\text{SC})(\text{WWR})$
February	OTTV = $10.75(U_w)(1 - \text{WWR}) + 3.96(U_f)(\text{WWR}) + 120.11(\text{SC})(\text{WWR})$
March	OTTV = $11.50(U_w)(1 - \text{WWR}) + 4.51(U_f)(\text{WWR}) + 118.66(\text{SC})(\text{WWR})$
April	OTTV = $11.62(U_w)(1 - \text{WWR}) + 4.68(U_f)(\text{WWR}) + 116.09(\text{SC})(\text{WWR})$
May	OTTV = $11.07(U_w)(1 - \text{WWR}) + 4.21(U_f)(\text{WWR}) + 113.99(\text{SC})(\text{WWR})$
June	OTTV = $11.05(U_w)(1 - \text{WWR}) + 4.25(U_f)(\text{WWR}) + 114.13(\text{SC})(\text{WWR})$
July	OTTV = $10.64(U_w)(1 - \text{WWR}) + 4.10(U_f)(\text{WWR}) + 110.62(\text{SC})(\text{WWR})$
August	OTTV = $10.58(U_w)(1 - \text{WWR}) + 4.13(U_f)(\text{WWR}) + 108.66(\text{SC})(\text{WWR})$
September	OTTV = $10.15(U_w)(1 - \text{WWR}) + 3.97(U_f)(\text{WWR}) + 104.58(\text{SC})(\text{WWR})$
October	OTTV = $10.61(U_w)(1 - \text{WWR}) + 4.11(U_f)(\text{WWR}) + 109.30(\text{SC})(\text{WWR})$
November	OTTV = $10.82(U_w)(1 - \text{WWR}) + 4.03(U_f)(\text{WWR}) + 117.12(\text{SC})(\text{WWR})$
December	OTTV = $10.50(U_w)(1 - \text{WWR}) + 3.77(U_f)(\text{WWR}) + 122.25(\text{SC})(\text{WWR})$
Annual	OTTV = $10.84(U_w)(1 - \text{WWR}) + 4.13(U_f)(\text{WWR}) + 114.65(\text{SC})(\text{WWR})$

Table 5
Regressed relationships for OTTV for schedule 3: department store

Month	Relationships
January	OTTV = $13.26(U_w)(1 - \text{WWR}) + 4.20(U_f)(\text{WWR}) + 162.35(\text{SC})(\text{WWR})$
February	OTTV = $13.16(U_w)(1 - \text{WWR}) + 4.21(U_f)(\text{WWR}) + 159.61(\text{SC})(\text{WWR})$
March	OTTV = $14.54(U_w)(1 - \text{WWR}) + 5.20(U_f)(\text{WWR}) + 163.36(\text{SC})(\text{WWR})$
April	OTTV = $14.59(U_w)(1 - \text{WWR}) + 5.38(U_f)(\text{WWR}) + 159.78(\text{SC})(\text{WWR})$
May	OTTV = $14.13(U_w)(1 - \text{WWR}) + 4.89(U_f)(\text{WWR}) + 158.49(\text{SC})(\text{WWR})$
June	OTTV = $13.93(U_w)(1 - \text{WWR}) + 4.83(U_f)(\text{WWR}) + 157.09(\text{SC})(\text{WWR})$
July	OTTV = $13.29(U_w)(1 - \text{WWR}) + 4.58(U_f)(\text{WWR}) + 150.94(\text{SC})(\text{WWR})$
August	OTTV = $13.19(U_w)(1 - \text{WWR}) + 4.65(U_f)(\text{WWR}) + 148.12(\text{SC})(\text{WWR})$
September	OTTV = $12.66(U_w)(1 - \text{WWR}) + 4.42(U_f)(\text{WWR}) + 141.82(\text{SC})(\text{WWR})$
October	OTTV = $13.39(U_w)(1 - \text{WWR}) + 4.67(U_f)(\text{WWR}) + 150.45(\text{SC})(\text{WWR})$
November	OTTV = $13.72(U_w)(1 - \text{WWR}) + 4.51(U_f)(\text{WWR}) + 160.73(\text{SC})(\text{WWR})$
December	OTTV = $12.88(U_w)(1 - \text{WWR}) + 3.91(U_f)(\text{WWR}) + 163.00(\text{SC})(\text{WWR})$
Annual	OTTV = $13.56(U_w)(1 - \text{WWR}) + 4.62(U_f)(\text{WWR}) + 156.30(\text{SC})(\text{WWR})$

where C_1–C_4 are coefficients, LPD the nominal lighting power density, EPD the equipment power density, VENT the ventilation load, calculated from the difference between the average enthalpy of exterior air and the reference enthalpy of interior air at 25 °C and relative humidity at 50%, OCCU is sensible and latent heat contributed by human occupants, and Storage is the storage load. The values of the five parameters were varied, each in a range shown in Table 6.

Table 6
Ranges of values of five parameters for parametric runs for CR

Parameters	Range of values
LPD (Wm^{-2} floor)	6–30
EPD (Wm^{-2} floor)	6–30
VENT (Wm^{-2} floor)	1.68–16.80
OCCU (Wm^{-2} floor)	2.64–26.38
Floor weight (kg m^{-2})	100–500

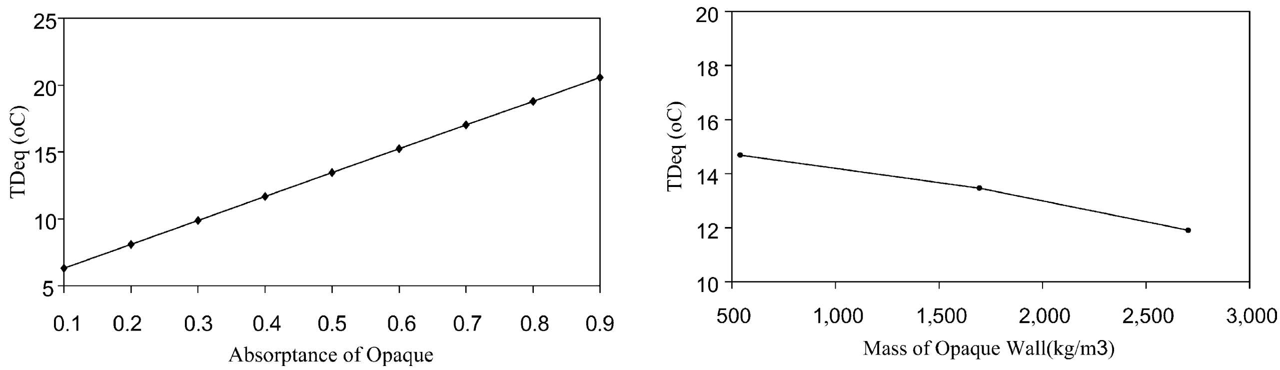

Fig. 5. The TD_{eq} values as functions of solar absorptance and mass of opaque wall.

Table 7
Regressed relationships between cooling requirements and OTTV, energy usage parameters and parameters related to occupancy

Item	Relationships	Correlation coefficient
Schedule 1	CR = (OTTV) + 0.94(LPD) + 0.98(EPD) + 0.41(VENT) + 0.92(OCCU) + 1.92	0.9969
Schedule 2	CR = (OTTV) + 1.02(LPD) + 1.02(EPD) + 0.36(VENT) + 0.92(OCCU) + 0.75	0.9979
Schedule 3	CR = (OTTV) + 0.94(LPD) + 0.98(EPD) + 0.45(VENT) + 0.97(OCCU) + 0.50	0.9965

In this set of parametric run, values relevant to external load and OTTV were kept constant. The value for OTTV in Eq. (5) was calculated by the resulting equation obtained from previous parametric runs. This resulting set of OTTV values was then used with the five sets of parameters (LPD, EPD, VENT, OCCU, and floor weight) and the calculated monthly CR to regress for the coefficients C_1–C_4. The resultant values are shown in Table 7.

The storage load for schedule 1 as shown in Table 7 is higher than those of other schedules, as the building in this scheduled is used during day time and closed on weekends and holidays. However, for the generic building model used, the effect of internal storage load seems rather small and insignificant. The resultant values for the coefficients of LPD, EPD, VENT, and OCCU show the extent each term contributes to CR. The values of the coefficients for LPD and EPD for schedule 2 exceed unity. This signifies that

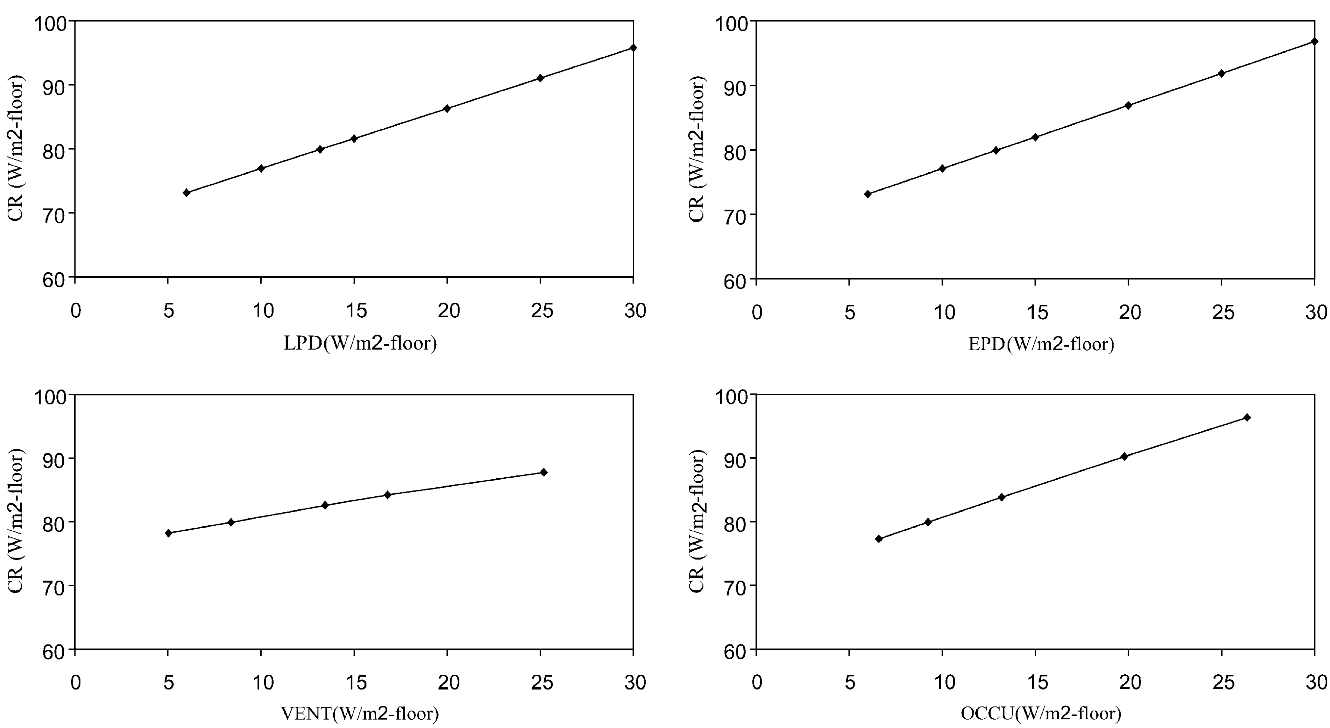

Fig. 6. Correlation between internal load and CR.

Table 8
Regressed relationships between cooling requirements and OTTV under new schedules

Schedule (h)	Relationships	Correlation coefficient
8:00–17:00	CR = (OTTV) + 0.94(LPD) + 0.98(EPD) + 0.41(VENT) + 0.92(OCCU) + 1.92	0.9969
7:00–18:00	CR = (OTTV) + 0.95(LPD) + 0.99(EPD) + 0.39(VENT) + 0.91(OCCU) + 1.99	0.9971
9:00–16:00	CR = (OTTV) + 0.92(LPD) + 0.98(EPD) + 0.41(VENT) + 0.93(OCCU) + 1.48	0.9967

probably an under-valued OTTV was used in the regression. Nevertheless, the correlation coefficients in these regressions exceed 0.99. The high values of the coefficients for LPD and EPD imply that lighting and equipment loads contribute significantly to CR. Fig. 6 exhibits linear relationships between CR and each of its components. These results reinforce the assertion made that CR is related linearly to the first degree to its components, even the heat transfer mechanisms include nonlinear relationships.

The following figure shows the effects of WWR and floor weight on the storage load. The values of WWR and SC were varied while the OTTV was kept constant by adjustment of the values of other components. The result shows that the storage load varies linearly with WWR. Higher value of WWR allows deeper penetration of solar radiation in to the building interior and higher level of accumulation of heat.

The floor weight was varied from 10 to 975 kg m^{-2} (the base-case value is 341.8 kg m^{-2}) in the parametric runs and the resultant relationship between storage load and floor weight is as shown. It is observed that storage load decreases when the weight of floor increases.

5.1. Sensitivity of change in schedule on coefficients of CR equation

In this study, the schedules were varied by extending the working hours 2 h from the normal working hours both in the morning and in the evening (from 8:00–17:00 h to 7:00–18:00 h) and reducing the working hours 2 h (to 9:00–16:00). Parametric runs were conducted for these new working schedules in order to test the sensitivities of the parameters to changes in the time schedule of office building. Table 8 shows the regressed relationships for the new schedules.

Table 9
Information of audited buildings

Parameters	Office	Hotel	Hospital	Department store
Number of stories	14	15	15	22
Floor area (m^2)	16,712	15,926	19,489	48,973
Ratio of wall area to floor area	0.40	0.29	0.59	0.23
WWR	0.33	0.36	0.23	0.61
LPD (Wm^{-2} floor)	14.64	5.45	11.93	12.54
EPD (Wm^{-2} floor)	20.80	0.80	3.45	20.69
VENT (Wm^{-2} floor)	8.40	8.40	8.40	8.40
OCCU (Wm^{-2} floor)	9.23	9.23	9.23	9.23
COP	1.49	2.54	2.45	2.55

The results show that there is a slight and insignificant change on the OTTV equation. These also show that the longer the operating hours of the building, the fuller contributions of lighting and equipment to CR.

6. Energy consumption models and their validation

It is postulated that energy consumption of a building over a period can be calculated from a relationship in the form of Eq. (3). To be precise, for each of our building model the applicable equation is:

$$\text{Energy consumption} = \left(\frac{\text{CR}}{\text{COP}} + \text{LPD} + \text{EPD}\right) \times \text{area of floor} \times \text{working hours} \quad (6)$$

Information from reports of energy audit taken in 1996 of each of type of commercial building were used for validation of Eq. (6). Summary information on each building appears in Table 9.

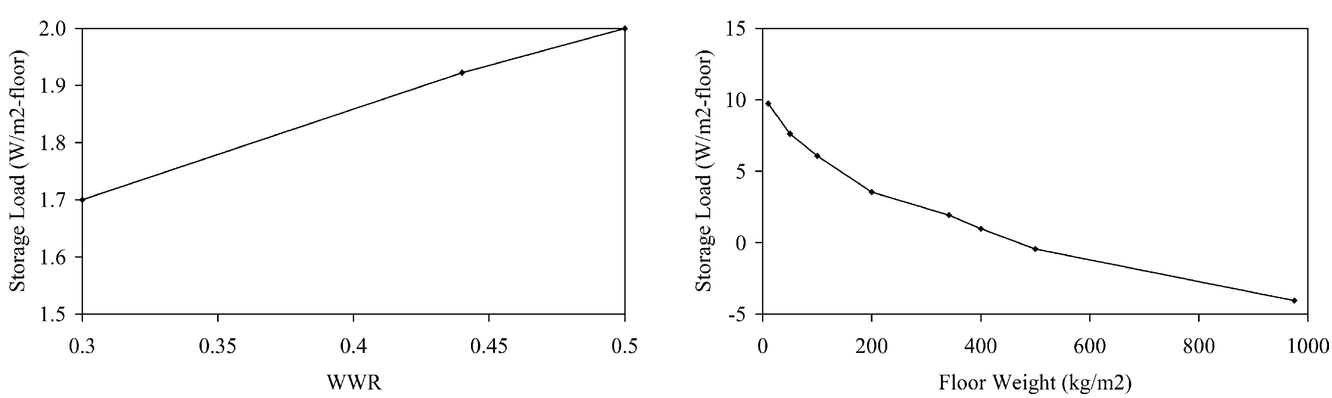

Fig. 7. Effects of WWR and floor weight on storage load.

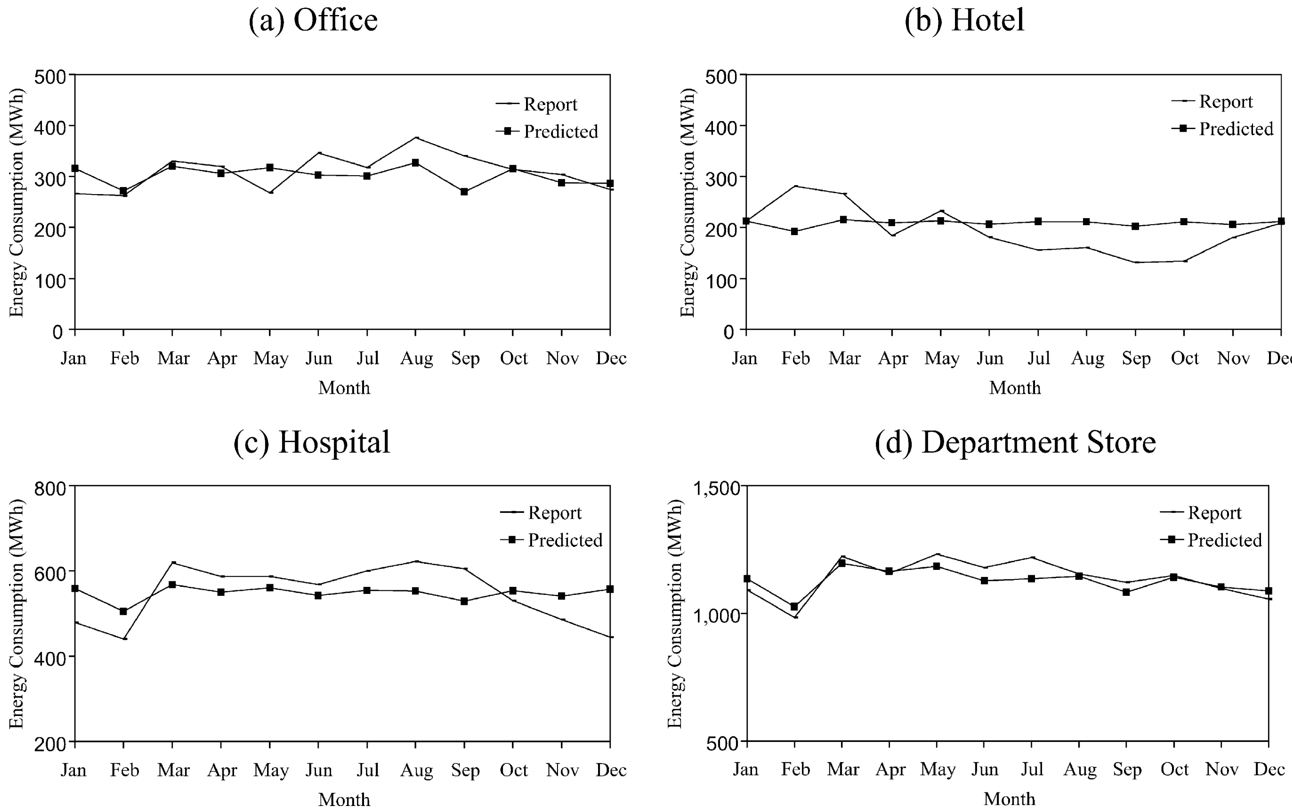

Fig. 8. Comparisons of monthly energy consumption.

The value of COP appearing in Table 9 was obtained from on-site measurement of the air-conditioning system and chilled water plant of the respective building. The values of TD_{eq}, DT, and SF in Tables 3–5 were used to calculate monthly and annual OTTV for each building. Parameter values in Table 7 were used in each CR equation for each building. Fig. 7 shows the graph of monthly energy consumption of each building calculated based on the resultant CR value and energy consumption Eq. (9). The figure also shows the graph of monthly energy consumption obtained from the energy audit report of each building. The graphs show good agreement between the results calculated by the models and those from audit reports. For office and department store buildings, very good agreement are obtained. For hotel and hospital buildings, more discrepancies on monthly values are observed. But for these latter buildings, the monthly occupancy figures of guests and patients were not known. Nevertheless, cumulative annual energy consumption from the model agrees very well with the value from energy audit report for each building Fig. 8.

7. Conclusion

The postulates on cooling requirement and energy consumption of the four types of commercial buildings are shown in this paper to be respectively verified through parametric runs using DOE-2 program and validated by energy audit reports of real buildings. The relationships postulated are simple and natural even though the dynamic relationships between the driving forces and resultant energy-related terms in a building are complex. It is expected that the results would contribute towards energy conservation efforts, both in works related to energy code compliance and in energy monitoring efforts.

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