CASE STUDY OF THE OPERATIONAL ENERGY CONSUMPTION AND CARBON EMISSIONS FROM A BUILDING IN NANJING BASED ON A SYSTEM DYNAMICS APPROACH

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ABSTRACT

Buildings are responsible for more than forty percent of global energy consumption and as much as one third of global greenhouse gas emissions. Meanwhile, the energy conservation and exhaust reduction of a building can be easily understood by accurately calculating a building's carbon emissions during its operational stage. In the present study, a system dynamics (SD) approach to calculate the energy consumption and carbon emissions from a building during its operational stage is quantitatively developed through a case study on an office building in Nanjing. The obtained results demonstrate that: a) the difference between the results of SD and that of EnergyPlus is so small that a SD approach is acceptable; b) the variation between the real monitored data and that of simulation by SD and EnergyPlus is reasonable; c) the physical meanings of the variables in the SD model are clear; d) the parameters of the SD model and the relationships between the variables can be determined by a qualitative-and-quantitative combined analysis.

KEYWORDS

operational; energy consumption; carbon emissions; buildings; system dynamics approach

1. INTRODUCTION

Buildings are responsible for more than 40 percent of the global energy used, and as much as one third of global greenhouse gas (GHG) emissions, both in developed and developing countries. In absolute terms, the Fourth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) estimated global building-related GHG emissions to be around 8.6 million metric tons CO_2 eqv in 2004. What is particularly worrying is the rate of growth of emissions: between 1971 and 2004, CO_2 emissions, including through the use of electricity

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in buildings, is estimated to have grown at a rate of 2.5% per year for commercial buildings and at 1.7% per year for residential buildings. Furthermore, the Buildings and Construction Sector is also responsible for significant non-CO_2 GHG emissions such as halocarbons, Chlorofluorocarbons (CFCs), and Hydrochlorofluorocarbons (HCFCs) (covered under the Montreal Protocol), and hydrofluorocarbons (HFCs), due to their applications for cooling, refrigeration, and in the case of halocarbons, insulation materials. Under the IPCC's high growth scenario, this figure could almost double by 2030 to reach 15.6 billion metric tons CO_2 eqv [1].

By far, the greatest proportion of energy is used during a building's operational phase. Though figures vary from building to building, studies suggest that over 80 percent of GHG emissions take place during this phase to meet various energy needs such as heating, ventilation, and air conditioning (HVAC), water heating, lighting, entertainment and telecommunications. A smaller percentage, generally 10 to 20 percent, of energy is consumed in materials manufacturing and transport, construction, maintenance and demolition [1-4]. Therefore, there is a huge potential for energy conservation and exhaust reduction during a building's operational stage.

The energy conservation and exhaust reduction of a building can be easily understood by accurately calculating a building's carbon emissions during its operational stage. In the present study, a model to clearly and accurately calculate the carbon emissions from a building during its operational stage is quantitatively developed through a case study on an office building in Nanjing; this method is based on a system dynamics approach.

2. LITERATURE REVIEW

Interest in the operational carbon emissions of buildings during their lifetime has increased in the last few years [5] and descriptive studies on residential and non-domestic buildings (primarily offices) have been conducted. The operational carbon emissions from buildings is the amount of carbon required to condition (heating, cooling, and ventilating), light the interior spaces, and to power equipment and other services; however, this amount varies considerably with different building use patterns, climate, season, and the efficiency of the building and its systems [6]. In a study on a Canadian office building, Cole and Kernan [6] concluded that the amount of operational carbon emissions is the largest component of the life-cycle carbon emissions. The study stated that for a building designed following conventional energy performance standards, the operational carbon emissions will increase its proportion of the life cycle carbon emissions as the building operational efficiency increases [6]. Sartori and Hestness [7] analyzed 60 building case studies and revealed that the operating carbon emissions represent by far the largest portion of the carbon demand in a building during its life cycle. The authors showed a linear relationship between the operating and total lifetime carbon emissions, which was valid for all the case studies regardless of the climate and other contextual differences. Thus, this result demonstrates the lifetime efficiency of low-carbon buildings compared with that of conventional buildings, even with a higher embodied impact.

Based on hour-by-hour dynamic modeling of heat flows in building mass configurations Dodoo et al. [8] calculated the energy saving benefits of thermal mass during the operation phase of the buildings. Their results indicated that the energy savings due to thermal mass is small and varies with the climatic location and energy efficiency levels of the buildings. A concrete-frame building has slightly lower space heating demand than a wood-frame alternative, due to the higher thermal mass of concrete-based materials. In fact, there is still an energy input requirement to heat concrete and keep it heated, and while there is a storage component if the heating source is removed, there is still an ongoing requirement for energy input to maintain temperature. A wood frame building has less thermal bridging and higher thermal resistance generally.

Mechri et al. [9] presented a new approach in which Analysis Of Variance (ANOVA) was used to identify the design variables that had the most impact on the variation of the building energy performance for a typical office building and to allocate the contribution of each variable to this variation. Moreover, the study addressed an important issue concerning the identification and the setting of a set of simple and concise variables that could be used during the conceptual design stage of office buildings. The analysis showed that the suggested approach could be useful for architects to evaluate the degree to which each design variable contributes to the variability of the building energy performance.

An integrated design tool was developed by combining a social cognitive optimization algorithm, an infrastructure model and a set of analysis modules to provide the technical design, the evaluation of greenhouse gas emissions and the financial appraisal for the scheme (Rees et al. [10]). The integrated design tool was applied to a new build scheme in the UK with a 60% target reduction of regulated emissions. It was shown that the optimal design and corresponding cost was sensitive to the year of build completion and to the assumptions applied when determining the emissions intensity of the marginal central generators.

Buildings worldwide account for a surprisingly high global energy consumption (40%) [1] and produce an increasingly large carbon footprint. The future sustainability of the building sector is therefore strongly dependent on installing energy-efficient technologies. However, even though these technologies are becoming more and more efficient, human behavior still plays an extremely important role in the overall building carbon emissions [11-13]. In another study [14], a model of occupant behavior within a building in relation to the operational carbon emissions and a building carbon emission model was proposed based on stochastic Markov models. This carbon emission model was used to predict possible energy saving gains from building retrofitting projects. The obtained results demonstrated that the proposed carbon emission model could learn occupant behavioral patterns from the building. Additionally, the model could reliably reproduce the result, predict the building carbon emission model and identify potential areas of energy waste.

Davis et al. [15] applied system dynamics (SD) to household energy consumption and coordinated various types of interventions. The following were the conclusions of the study: (a) an SD approach proved useful in advancing a non-traditional perspective when, for historical and economic reasons, data were not abundantly available; (b) some skepticism regarding an SD model might be expected in areas where traditional models were heavily quantitative; and (c) a statistical comparison of the model results via empirical data might be an effective tool in reducing such skepticism. Hiroshi [16] applied the SD approach to calculate the carbon emissions for the entire life cycle of a building. The author performed the simulation based on investigating architecture design strategies, which predicted and reduced the environmental loads of several types of construction and building materials. As a result, houses with a long service life and high energy efficiency were more effective than traditional houses in terms of life-cycle assessment.

3. METHOD—SYSTEM DYNAMICS APPROACH

3.1 Introduction

The system dynamics (SD) approach is a modeling method developed from the systems thinking ideas [17]. System dynamics is based on the original work of Jay Forrester who defined it as "the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy" [18]. SD models depend on the structure of the model, time lags, and amplification, which occurs through feedback [18], and allows examination of the long-term behavior of complex systems [19].

The SD approach allows the building to be modeled as a feedback system and can be used to simulate the interactions amongst the various building sub-systems. It is applicable to building system simulation because it is ideal for situations where the system to be modeled is extremely complex, highly dynamic (in time and/or in space), or contains large numbers of feedbacks, and its focus is on the basic structure of the system, allowing for highly uncertain variables to be included [17,20]. Its focus is on the basic structure of the system, allowing for incorporation of 'soft' factors that can help to capture human behavior of the building occupants [21], and for other highly uncertain variables to be usefully included. Incorporation of these soft factors will be important in a building system model to address the occupants' perceptions of and reactions to changes in a building's design and operation. These reactions will determine, to some extent, how building occupants behave (e.g., whether they keep the windows closed when the air conditioning is running). SD allows quantification of system behavior without necessarily requiring a high level of numerical accuracy in the model, as long as the model structure is well-defined [18]. The SD method facilitates the search for leverage points through the use of sensitivity analyses [22], and allows simulation experiments to be conducted on virtual buildings or retrofits [20]. A model constructed using the SD approach will also be transparent to users [23] and easily manipulated. Users will not need to be system dynamics experts to use the model or to make changes to the parameters within it [17]. The main difficulties encountered in applying the SD approach arise from difficulties in identifying truly dynamic feedback relationships within buildings' systems [24].

A SD model is "an interlocking set of differential algebraic equations developed from a broad spectrum of relevant measured and experiential data" [25]. The equations are represented by a diagram, as shown in Figure 1, consisting of three element types: (1) stock (or level) elements (also called state variables); (2) flow elements (or rates); and (3) auxiliary variables and constants [23]. Stock variables accumulate the flow variables, and auxiliary variables modify the flow variables. In the simple model in Figure 1, the auxiliary variable is set to some constant, C. The inflow variable is then some function f of C. Since in Figure 1 Outflow depends on Stock, the stock variable is defined as some function g of Stock. The stock variable, then is the sum of the initial value of the stock and the inflow rate integrated over time, less the outflow rate integrated over time [17]. The definitions of the model variables in Figure 1 are given in Equations 1 through 4.

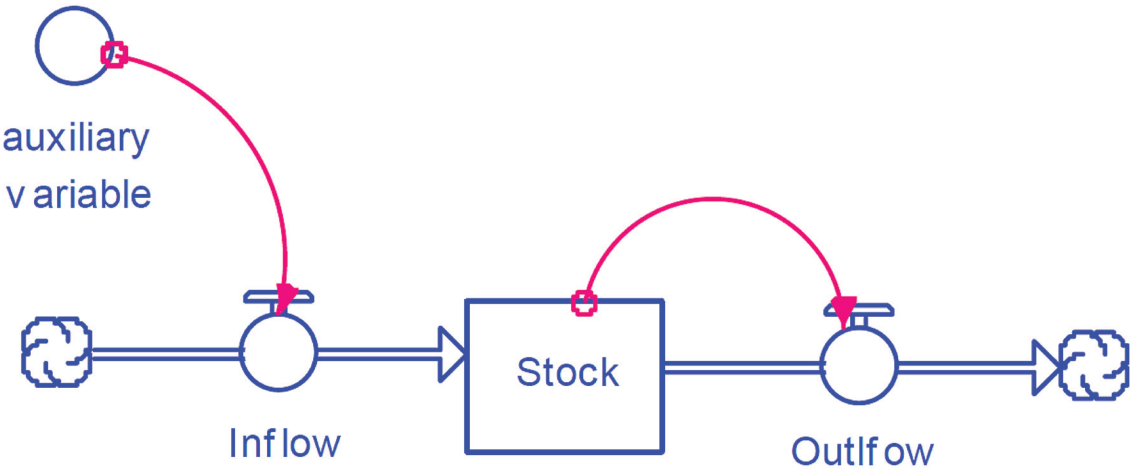
$$auxiliary\_variable = C \quad (1)$$

$$Inflow = f(C) \quad (2)$$

$$Outflow = g(Stock) \quad (3)$$

$$Stock(t) = Stock(t-dt) + Inflow*dt - Outflow*dt \quad (4)$$

FIGURE 1. Structure of a SD Model



3.2 Simple exploratory building system interaction model

The model described in this section is developed to explore the concept of using a system dynamics model to make decisions regarding building design to minimize the effects of energy consumption. This model is not intended to provide specific, detailed engineering design data regarding the building design. It is common in the SD method to develop a rough model, followed by iterative refinements [17]. "One of the first steps is the model that is fashioned merely to the best of the investigator's immediate ability. The emphasis is on plausibility, not accuracy. Defending the detailed accuracy of assumptions is secondary to emphasizing what the model can teach" [18]. This simple model is merely developed for the purpose of examining the feasibility of using the SD method to model a building and of integrating the thermal admittance method with a SD model of a building. It is used as a starting point for construction of the model developed for this study.

FIGURE 2. SD building model energy system sector

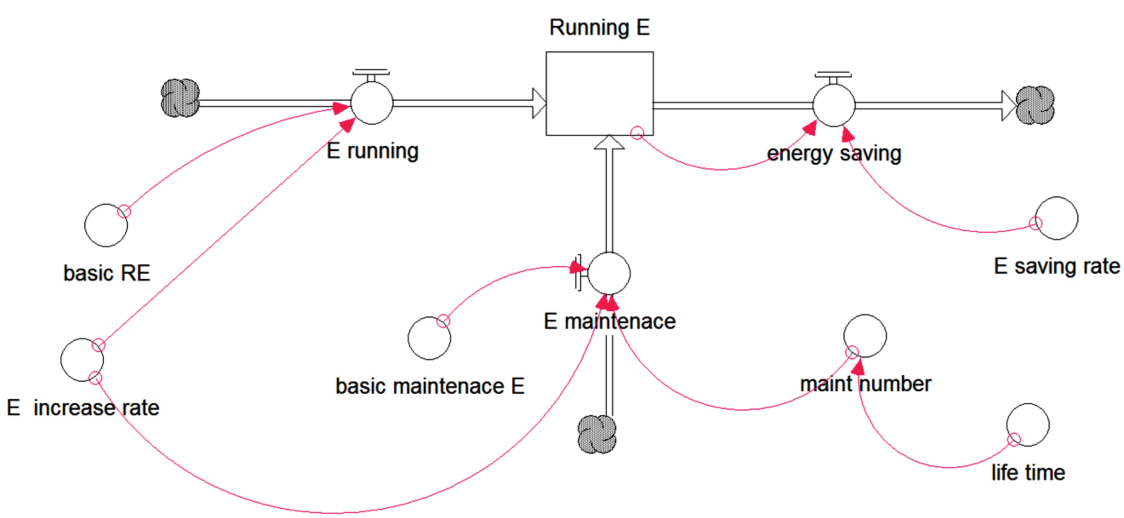


Figure 2 shows the simple model of a building's energy system, modeled using STELLA® software from isee systems [26]. This simple model is developed to simulate a single-zone building whose operational stage is 50 years.

The *Running_E* stock variable tracks the amount of energy consumption in the building. It is defined in Equation 5.

$$Running\_E(t) = Running\_E(t - dt) + (E\_running + E\_maintenace - energy\_saving) * dt \qquad (5)$$

Where, INIT Running_E = 0

The flows into and out of the '*Running_E*' stock are given in Equations 6, 7, and 8.

The '*E_running*' flow variable is defined for energy demand for running a building. It is defined in Equation 6.

$$E\_running = basic\_RE*(1+E\_\_increase\_rate) \qquad (6)$$

The '*E_maintenace*' flow variable is defined for energy demand for maintaining a building. It is defined in Equation 7.

$$E\_maintenace = basic\_maintenace\_E*(1+E\_\_increase\_rate)*maint\_number \qquad (7)$$

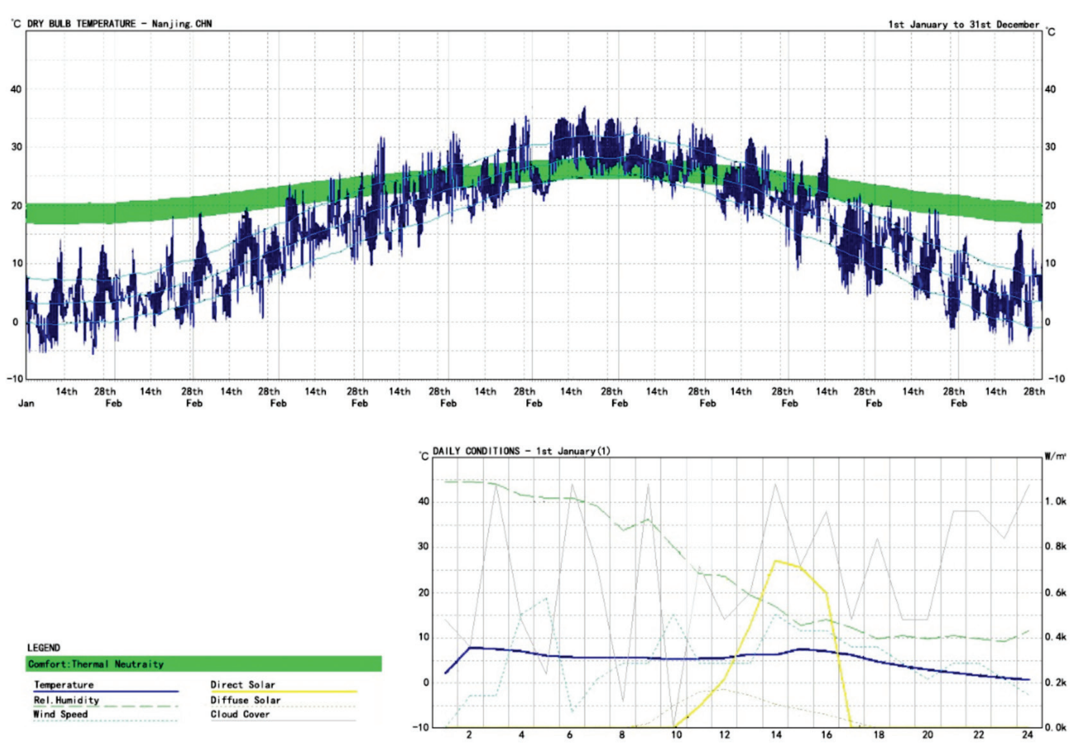
The '*energy_saving*' flow variable is the amount of energy saving by adopting energy-efficiency technologies. It is defined in Equation 8.

$$energy\_saving = Running\_E*E\_saving\_rate \qquad (8)$$

4. CASE STUDY DESCRIPTION

The Run Run Shaw Architectural building (RRSAB) (used as the case study in this paper) is an office building located at Southeast University, Nanjing. Nanjing lies on the geographical coordinates of 32° N and 118.8° E and is in a region with hot summers and cold winters. The

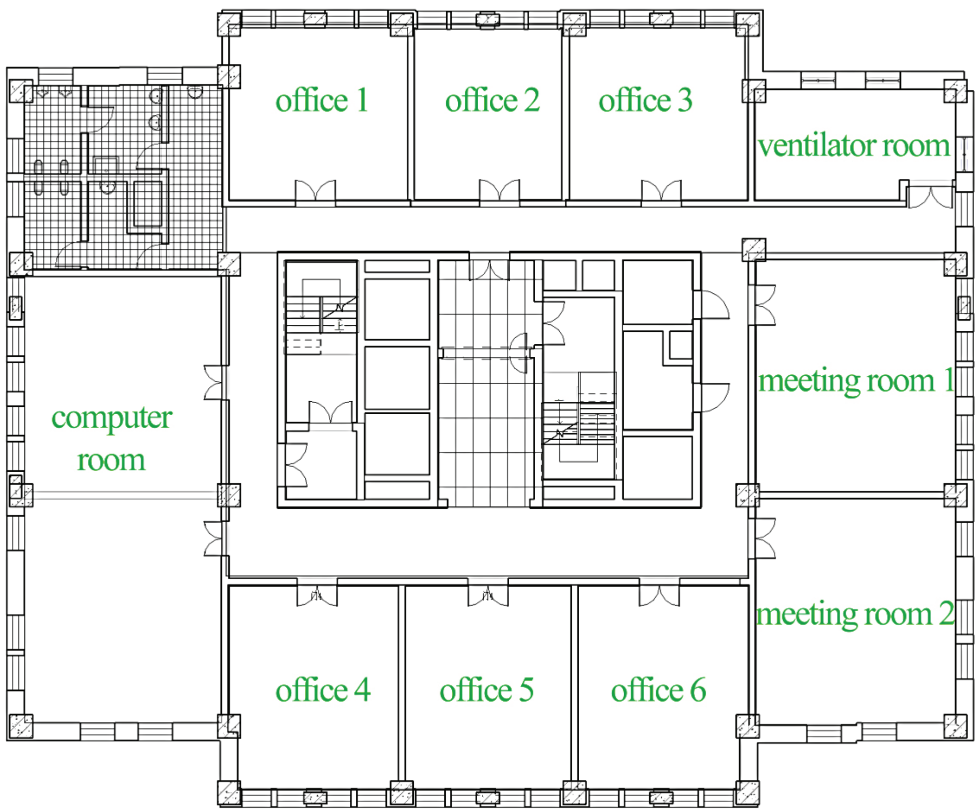
FIGURE 3. Annual meteorological data of Nanjing in a TMY



climatic characteristics of Nanjing are as follows: the temperature is the lowest and the wind speed is relatively high in the cold wintry months of January and February; the temperature is the highest and the wind speed is relatively low in the hot summer months of July and August. Figure 3 shows the annual meteorological data of Nanjing in a typical meteorological year (TMY) [27].

The fifth floor of the RRSAB was used as the example in this study. Figure 4 shows the floor plan of this floor. Table 1 lists the components of the building envelope and the details of the occupants and equipment. The air conditioning calculation parameters and the loads from the occupants, lighting and equipment (listed in Tables 2 and 3, respectively) were all in compliance with the requirements of the Design Standard for Energy Efficiency of Public Buildings (GB50189-2005) [28]. The air conditioning system is an air-cooled heat pump unit with a coefficient of performance (COP) of 2.60. The service life of the building is 50 years.

FIGURE 4. Floor plan of the fifth floor of the RRSAB



In this case, the calculation is based on the following assumptions:

a) The operative temperature in adjoining rooms is equal to that for the module under consideration and hence heat flow occurs only through the outside window–wall. This assumption is acceptable because rooms and aisles are air conditioning zones in typical office buildings in Nanjing.

b) The thermal transmittance of the window frame is equal to that of the glass.

c) There are no internal blinds, therefore the solar gain to the air node is zero.

TABLE 1. Components of the building envelope and details of the occupants and electrical equipment on the fifth floor of the RRSAB.

Categories	Descriptions of the components, occupants and electrical equipment
External walls	10 mm face brick, 10 mm lime mortar, 10 mm cement mortar, 500 mm brick, 19 mm lime mortar and 1 mm coating
Internal walls	1 mm coating, 19 mm lime mortar, 200 mm brick, 19 mm lime mortar and 1 mm coating
Floors and ceilings	15 mm white cement and white pebble stones, 20 mm lime mortar and 120 mm reinforced concrete
Windows	Aluminum alloy windows (1020 mm × 1800 mm)
Occupants	90 occupants; 70 W/occupant; working hours: 8:00 – 23:00
Office and electrical equipments	31 W/m^2

TABLE 2. Indoor air conditioning calculation parameters.

Room types	Summer		Winter	
	Temperature (℃)	Humidity (%)	Temperature (℃)	Humidity (%)
Offices	26	60	20	≥30
Conference rooms	26	60	18	≥30
Computer rooms	27	60	18	≥30

TABLE 3. Loads from occupants, lighting and equipment.

Room types	Per capita area (m^2/ occupant)	Lighting (W/ m^2)	Heat gain from equipment (W/ m^2)	Heat gain from occupants (W/ m^2)
Offices	5	11	20	12
Conference rooms	3	15	5	20
Computer rooms	4	11	40	14

Note: Per capita area (m^2/occupant) refers to the area that each occupant occupies.

According to CIBSE Guide A [29], thermal admittance (Y-value) is the rate of flow of heat between the internal surfaces of the structure and the environmental temperature in the space, for each degree of deviation of that temperature about its mean value. The associated time dependency takes the form of a time lead. Thermal transmittance (U-value) is the thermal transmission through unit area of a given structure, divided by the difference between the effective ambient temperature on either side of the structure under steady state conditions. For thin structures of low thermal capacity, the Y-value is equal in amplitude to the U-value and has a time lead of zero. In the case of an exciting frequency with a period of 24 hours the amplitude tends towards a limiting value for thicknesses greater than about 100 mm. For multi-layered structures, the Y-value is primarily determined by the characteristics of the materials in the layers nearest to the internal surface. For example, the admittance of a heavy concrete slab construction lined internally with insulation will be close to the value for the insulation alone, whereas placing the insulation within the construction, or on the outside surface, will result in an admittance that differs little from that for the uninsulated slab.

Therefore, in this study, U is used to calculate both the '*heating load*' under *winter heating design conditions* which are assumed to be a *steady state model* and the '*mean cooling load*' under *summer cooling design conditions* which are conventionally assumed to be a *periodic model* model. Y is used to calculate the '*alternating convective cooling load*' under *summer cooling design conditions* which are conventionally assumed to be a *periodic model*. For more details, please see Section 5. Table 4 lists the thermal performance parameters of the building envelope of the floor.

TABLE 4. Thermal performance parameters of the building envelope of the fifth floor of the RRSAB.

Categories	A (m^2)	U (W/m^{2}K)	$A\times U$ (W/K)	Y (W/m^{2}K)	$A\times Y$ (W/K)	f	Delay time (h)
External walls	14.256	0.77	10.977	5.070	72.278	0.01	9
Internal walls	79.2	-	-	5.130	406.296	-	-
Floors	48	-	-	4.940	237.12	-	-
Ceilings	48	-	-	4.940	237.12	-	-
Windows	7.344	6.000	44.064	6.000	44.064	1	0.49
Sum	● A=196.8， ● (AU)=55.041，● (AY)=996.878						

Note:

a) Σ (AU) is calculated over surfaces through which heat flow occurs. There would not be a U value because of no heat flow occurrence between internal walls according to the assumptions—the operative temperature in adjoining rooms is equal to that for the module under consideration.

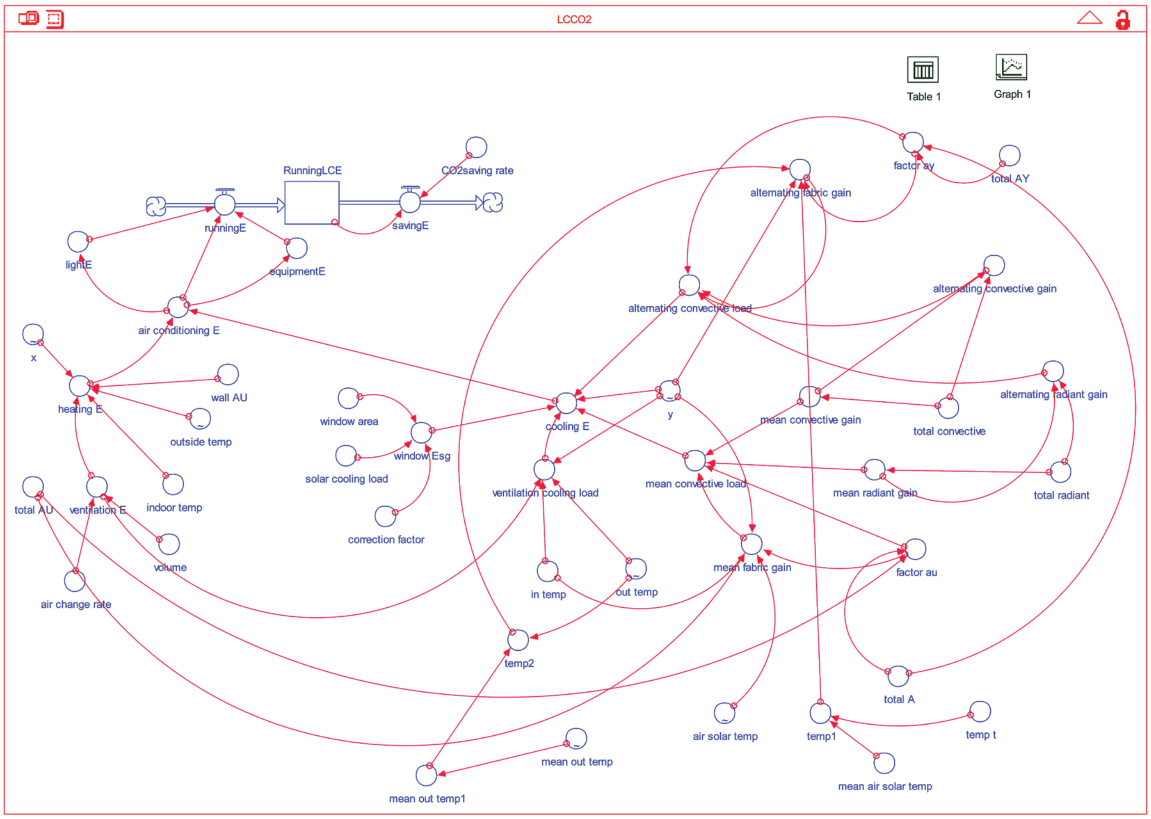
b) Σ (AY) is calculated over all surfaces. There would be a Y value because there is heat flow occurrence between the internal surfaces of the structure and the environmental temperature in the space according to the periodic model of CIBSE Guide A [29].

c) The decrement factor is the ratio of the rate of heat flow through the structure, due to variations in the external heat transfer temperature from its mean value with the environmental temperature held constant, to the steady state conduction. The associated time dependency takes the form of a time lag. For thin structures of low thermal capacity, the amplitude of the decrement factor is unity and the time lag zero. The amplitude decreases and the time lag increases with increasing thermal capacity.

5. DEVELOPMENT OF THE ENERGY CONSUMPTION AND CARBON (CO2) EMISSIONS CALCULATION MODEL FOR THE BUILDING DURING ITS OPERATIONAL STAGE

Generally, the annual heating and cooling load can be obtained from superimposing the air conditioning cooling load in the summer and the heating load in the winter. Since electricity is used in this region of China, the electricity consumption of the air conditioning system can be obtained based on the heating and cooling loads of the air conditioning system and their energy efficiency ratio. The operational stage is then divided into summer and winter seasons. The equations of the thermal admittance method are converted to SD format. The hourly carbon emissions model can then be developed using STELLA® software from isee systems [26] (Figure 5).

FIGURE 5. The SD model of the hourly simulation in Stella.



(Notes: LP: lighting power per unit area; EP: office equipment power per unit area; wall AU: the sum of the product of the wall body area and heat transfer coefficient; outside temp: outdoor temperature; indoor temp: indoor temperature; air change rate: air change rate; window Esg: cooling load caused by windows; ventilation cooling load: cooling load caused by ventilation; mean convective load: mean convective load; alternating convective load: swing convective load; mean fabric gain: mean heat gain from the building envelope; mean out temp: daily mean outdoor temperature; temp2: difference between outdoor temperature and mean outdoor temperature; air solar temp: outdoor sol-air temperature; mean air solar temp: mean outdoor sol-air temperature; light E: energy consumption of lighting: equipment E: energy consumption of power equipment; air conditioning E: energy consumption of the air conditioning; Running LCE: energy consumption during building's operational stage; x and y represent either 1 or 0: 1 indicates that the load at the given instant is cumulative, and 0 indicates that the load at the given instant is not cumulative.)y.

5.1 Total energy consumption during operational stage

Figure 5 shows the SD model of the hourly simulation in Stella. The '*RunningLCE*' stock variable tracks the amount of energy consumption during building's operational stage, Wh. It is defined in Equation 9.

$$RunningLCE(t) = RunningLCE(t - dt) + (runningE - savingE) * dt \quad (9)$$

Where, INIT *RunningLCE* = 0

The flows into and out of the '*RunningLCE*' stock are given in Equations 10 and 11.

5.2 Energy saving

The '*savingE*' flow variable is the amount of energy saving by adopting energy-efficiency technologies, W. It is defined in Equation 10.

$$savingE = RunningLCE*CO2saving\_rate \quad (10)$$

5.3 Energy demand

The '*runningE*' flow variable is defined for energy demand for running a building, W. It is defined in Equation 11.

$$runningE = air\_conditioning\_E+equipmentE+lightE \quad (11)$$

Where, the '*lightE*' variable is the amount of energy consumption of room lamps and lanterns, W, which is defined in Equation 12; the '*equipmentE*' variable is the amount of energy consumption of elevators, office and other electrical equipments, W, which is defined in Equation 13; the '*air_conditioning_E*' variable is the amount of energy consumption of the air conditioning, W, which is defined in Equation 14.

5.3.1Energy consumption of lighting and equimpment

*lightE = Nominal power factor of room lamps and lanterns * usage time of room lamps and lanterns* (12)

equipmentE = eleavtorE+office equipmentE+other electrical equipmentE (13)

Where,

*eleavtorE=Nominal power factor of elevator * usage time of elvator*

*office equipmentE = Nominal power factor of office equipment * usage time of office equipment*

*other electrical equipmentE = Nominal power factor of other electrical equipment * usage time of other electrical equipment*

5.3.2 Energy consumption of air conditioning

$$air\_conditioning\_E = cooling\_E+heating\_E \quad (14)$$

Where, the '*cooling_E*' variable is the total sensible cooling load to the air node, W, which is defined in Equation 15; the '*heating_E*' variable is the total heat loss in winter, W, which is defined in Equation 29.

5.3.2.1 Cooling loads

$$cooling\_E=y*(window\_Esg+ventilation\_cooling\_load+mean\_convective\_load+alternating\_convective\_load) \quad (15)$$

Where, the '*y*' variable is the season factor, which is 1 in summer, but it is zero in other seasons; the '*window_Esg*' variable is the cooling loads through windows and blinds, W, which is defined in Equation 16 [29]; the '*ventilation_cooling_load*' variable is the load due to infiltration, W, which is defined in Equation 17; the '*mean_convective_load*' variable is the mean convective cooling load, W, which is defined in Equation 19 [29]; the '*alternating_convective_gain*' variable is the alternating component of the convective gain, W, which is defined in Equation 24 [29].

5.3.2.1.1 Cooling loads through windows and infiltration

$$window\_Esg = window\_area*solar\_cooling\_load*correction\_factor \quad (16)$$

$$ventilation\_cooling\_load = y*ventilation\_E*(out\_temp-in\_temp) \quad (17)$$

Where, the '*ventilation_E*' variable is the ventilation conductance, W, which is defined in Equation 18.

$$ventilation\_E = air\_change\_rate*volume/3 \quad (18)$$

5.3.2.1.2 Mean convective cooling load

The '*mean_convective_load*' variable is the mean convective cooling load, W, which is defined in Equation 19[29].

$$mean\_convective\_load= mean\_fabric\_gain+1.5*factor\_au*mean\_radiant\_gain+mean\_convective\_gain-0.5*mean\_radiant\_gain \quad (19)$$

Where, the '*mean_fabric_gain*' variable is the mean fabric gain to the air node, W, which is defined in Equation 20 [29]; The '*factor_au*' variable is the room conduction factor with respect to the air node, which is defined in Equation 21; the '*mean_radiant_gain*' variable is the daily mean radiant gain, W, which is defined in Equation 22 [29]; the '*mean_convective_gain*' variable is the daily mean convective gain W, which is defined in Equation 23 [29].

$$mean\_fabric\_gain = y*factor\_au*total\_AU*(air\_solar\_temp-in\_temp) \quad (20)$$

$$factor\_au = (4.5*total\_A)/(4.5*total\_A+total\_AU) \quad (21)$$

Where, the '*total_A*' is the sum of surface area, m^2; the '*total_AU*' is the sum of the products of surface area and corresponding thermal transmittance over surfaces through which heat flow occurs, W/K.

$$mean\_radiant\_gain = total\_radiant*16/24 \quad (22)$$

$$mean\_convective\_gain = total\_convective*16/24 \quad (23)$$

5.3.2.1.3 Alternating convective cooling load

The '*alternating_convective_load*' variable is the alternating component of the convective cooling load, W. It is defined in Equation 24[29-31].

$$alternating\_convective\_load= alternating\_fabric\_gain+1.5*factor\_ay*alternating\_radiant\_gain+alternating\_convective\_gain-0.5*alternating\_radiant\_gain \quad (24)$$

where, the '*alternating_fabric_gain*' is the alternating component of the fabric gain to the air node, W, which is defined in Equation 25[29]; the '*factor_ay*' is the room admittance factor with respect to operative temperature, which is defined in Equation 26; the '*alternating_radiant_gain*' is the alternating component of the radiant gain, W, which is defined in Equation 27; and the '*alternating_convective_gain*' is the alternating component of the convective gain, W, which is defined in Equation 28.

$$alternating\_fabric\_gain = y*factor\_ay*(0.10977*temp2+44.064*temp1) \quad (25)$$

The '*factor_ay*' variable is the room admittance factor with respect to the air node, which is defined in Equation 26.

$$factor\_ay = (4.5*total\_A)/(4.5*total\_A+total\_AY) \quad (26)$$

where,

$$alternating\_radiant\_gain = total\_radiant-mean\_radiant\_gain \quad (27)$$

Where, the '*total_radiant*' is the sum of the radiation part of the heat gain from the room occupants and that from the room equipment, W; the '*mean_radiant_gain*' is the daily mean radiant gain, W, which is defined in Equation 22;

$$alternating\_convective\_gain = total\_convective - mean\_convective\_gain \quad (28)$$

Where, the '*total_convective*' include the convective part of the heat gain from the room occupants and that from the equipment in the room, W; the '*mean_convective_gain*' is the daily mean convective gain, W, which is defined in Equation 23.

5.3.2.2 Heating load

The '*heating_E*' variable is the total heat loss in winter, W, which is defined in Equation 29 [29].

heating_E = x(wall_AU+ventilation_E)*(indoor_temp-outside_temp)* (29)

Where, the '*x*' variable is the season factor, which is 1 in winter, but it is zero in other seasons; the '*wall_AU*' is the products of surface area and corresponding thermal transmittance over surfaces through which heat flow occurs, W/K; the '*ventilation_E*' variable is the ventilation conductance, W, which is defined in Equation 18.

5.4 Carbon emissions

The case example for this study was located in Nanjing, China, which is hot in the summer and cold in the winter. The energy source during the building operational stage is electricity only. Therefore, only the carbon emissions generated by electricity consumption need to be calculated, using the following formula:

*RunningLCC(t)=RunningLCE(t)*EFelectricity* (30)

Where, the '*RunningLCC(t)*' variable is the amount of carbon emissions during building's usage stage, t; the '*RunningLCE*' variable is the amount of energy consumption during building's operational stage, Wh; the '*EFelectricty*' is the operating margin emission factor for electricity that is 0.8244 in Nanjing according to the 2012 Baseline Emission Factors for Regional Power Grids in China [32].

6. RESULTS AND DISCUSSIONS

In order to verify whether the SD approach is suitable for simulating the energy consumption and carbon emissions by buildings, we used SD and EnergyPlus (EP) [33] to calculate these data of the fifth floor of the RRSAB. EP is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO).

Table 5 lists the simulation results of the electricity consumption and carbon emissions in each room.

Table 5 shows that the difference between the results of SD and that of EP is so small that the SD model is acceptable.

The RRSAB had a set of energy consumption monitoring systems, and its monitoring results are shown in Figures 6 and 7.

Unfortunately, there was no datum for July in the figure. But we can adopt the same datum as that of August because July and August were the two hottest months during the 2010-2011 years in Nanjing. From Figure 6, the energy consumption of air conditioning from November 2010 to October 2011 can be calculated to be 59.84 (=5.37+4.36+6.09+3+2.15+0.16+2.32+3.95+14.7+14.7+2.88+0.16) MWh. From Figure 7, the energy consumption of lighting and equipment from November 2010 to October 2011 can be calculated to be

TABLE 5. Simulation results of the electricity consumption and carbon emissions of the fifth floor of the RRSAB.

Rooms	Annual energy consumption (MWh)			Annual carbon emissions (t)			Fifty-year carbon emissions (t)		
	SD	EP	EP-SD	SD	EP	EP-SD	SD	EP	EP-SD
Office 1	5.52	5.82	0.30	4.56	4.80	0.24	227.84	239.90	12.06
Office 2	5.28	5.50	0.22	4.36	4.53	0.18	217.93	226.71	8.78
Office 3	5.52	5.68	0.16	4.56	4.68	0.13	227.84	234.13	6.29
Office 4	6.91	7.02	0.11	5.70	5.79	0.08	285.21	289.36	4.15
Office 5	6.86	6.91	0.05	5.66	5.70	0.03	283.15	284.83	1.68
Office 6	6.91	7.02	0.11	5.70	5.79	0.08	285.21	289.36	4.15
Conference room 1	4.42	4.45	0.03	3.65	3.67	0.02	182.44	183.43	0.99
Conference room 2	5.09	5.05	-0.04	4.20	4.16	-0.04	210.09	208.16	-1.93
Ventilator room	11.04	11.12	0.08	9.11	9.17	0.05	455.68	458.37	2.69
Computer room	35.66	35.25	-0.41	29.44	29.06	-0.38	1471.87	1453.01	-18.86
Restrooms	0.47	0.47	0.00	0.39	0.39	0.00	19.40	19.37	-0.03
Elevator landing	4.14	4.14	0.00	3.42	3.41	0.00	170.88	170.65	-0.23
The sum of the absolute values	97.82	98.43	1.51	80.75	81.15	1.23	4037.52	4057.28	61.86

Notes: The energy used for operating the elevators and the pump in the restrooms was not included in the calculation due to it being impossible to evenly distribute the energy consumption of each floor.

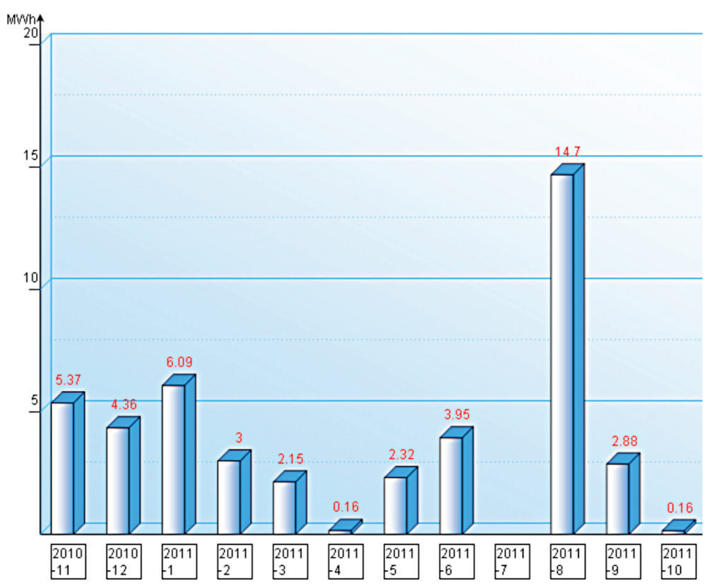
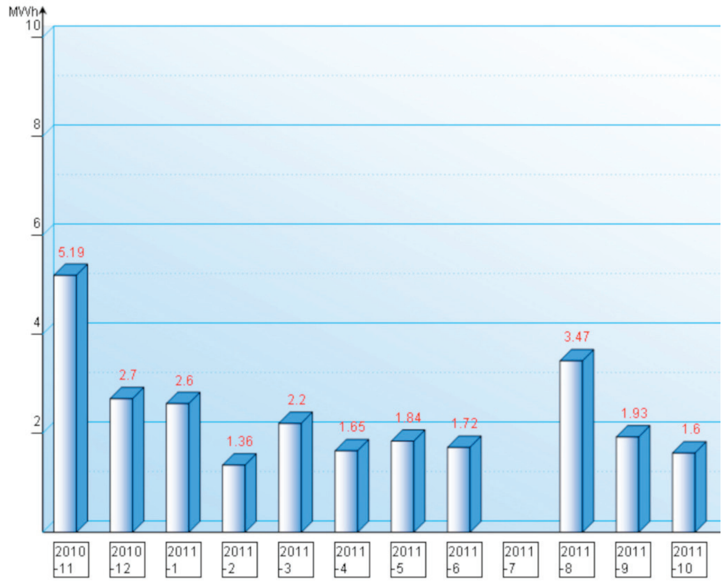


FIGURE 6. Energy consumed by the air conditioning of the fifth floor of the RRSAB.

FIGURE 7. Energy consumed by the lighting and equipment of the fifth floor of the RRSAB.



29.73 (=5.19+2.7+2.6+1.36+2.2+1.65+1.84+1.72+3.47+3.47+1.93+1.6) MWh. Therefore, the annual (from November 2010 to October 2011) energy consumption of the fifth floor of the RRSAB was 89.57 (=59.84+29.73) MWh.

The difference between the simulation result of 98.43 MWh in EP and the actual monitored datum of 89.57 MWh is 8.86 MWh, whereas the difference between the simulation result of 97.82 MWh in SD and the actual monitored datum of 89.57 MWh is 8.25 MWh. The difference between the 98.43 MWh of EP and the 97.82 MWh of SD is only 0.61 MWh.

The primary reasons for the difference between the simulated and monitored data are as follows. Firstly, several parameters in the simulation were averages, such as the solar cooling load, which was caused by windows, and these variables are related to the orientation of the windows and solar radiation. Secondly, human factors that affect energy consumption were not considered in the simulation. Thirdly, there was also energy consumed in the simulation in the transient seasons, i.e., April and October, when air conditioners were not actually on. Furthermore, the simulation in EP and SD both used the climate data from a typical year, which were not the same as that of the actual monitored climate. Therefore, more accurate results would be obtained if the data input into the SD model corresponded well with the actual data.

The objective of this paper is to verify whether the SD approach is suitable for simulating the energy consumed by buildings. The importance is not the accuracy of the SD calculation but to incite discussions and to study how to use this new approach. The above results and discussions demonstrate that SD can calculate the energy consumed by buildings and can obtain accurate results. Moreover, based on Figure 5, the SD approach has the following advantages:

a) The physical meanings of the variables in the model are clear. The relationships between the variables are also clear and intuitive. For example, the relationship between the cooling and heating loads of the air conditioning and the causes are extremely clear. Therefore, users can easily develop a model and adjust its parameters without advanced knowledge in system dynamics.
b) The parameters of the model and the relationships between the variables can be determined by a qualitative-and-quantitative combined analysis. The SD model consists of

the structural model (the flow chart of the system) and the mathematical model (the relationship of the model); therefore, the structural and mathematical models collectively determine the relationships among factors of the described object.

7. CONCLUSIONS

Currently, buildings are responsible for more than forty percent of global energy consumption and as much as one third of global greenhouse gas emissions, both in developed and developing countries. At the same time, the energy conservation and exhaust reduction of a building can be easily understood by accurately calculating a building's carbon emissions during its operational stage. Therefore, the SD approach is presented to simulate the energy consumption and carbon emissions of a building. Based on the above results and discussions, the following conclusions can be obtained:

a) The difference between the results of SD and that of EP is so small that the SD approach is acceptable.
b) The variation between the real monitored data and that of simulation by SD and EP is reasonable.
c) The physical meanings of the variables in the SD model are clear.
d) The parameters of the SD model and the relationships between the variables can be determined by a qualitative-and-quantitative combined analysis.

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