AN INTERACTIVE DESIGN ADVISOR FOR ENERGY EFFICIENT BUILDINGS

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ABSTRACT

This paper presents a holistic evaluation model that assists in designing energy efficient buildings. The model is based on computer-designer interaction. Here, the designer suggests a range of design alternatives, and in turn, the computer evaluation model generates a matrix of design solutions and performs various environmental simulations. The performances of the various design solutions are then analyzed to derive relationships that explain the impact that the different building components have on energy consumption. The relationships are represented in the form of statistical relations and interactive data charts.

The evaluation model was tested and used to evaluate an energy efficient house. The designer of this house implemented Strategies for integrating solar radiation, thermal mass, thermal insulation, and air ventilation to conserve energy. A field study and computer simulation were conducted to monitor the actual performance of the house, and to validate the evaluation model results. The research derived mathematical relations between thermal mass, thermal insulation, solar radiation and natural ventilation and the resulted energy consumption. The research also suggests general design guidelines to improve the energy performance of buildings, and to enhance thermal comfort.

KEYWORDS

holistic approach, thermal, energy, simulation, evaluation

BACKGROUND

Environmental comfort, economy, and energy conservation are among the major functional considerations in buildings. Many studies have been conducted to predict the contribution of each of major building components to energy conservation (ASHRAE, 1987). These studies resulted in general rules and design guidelines, which are intended to improve building energy performance in standard building designs. Field experiments and computer simulations were also used to determine and predict building performance, define preferred building design solutions, and suggest new building design alternatives. The goal of much of this work was to help the designer include energy conservation as an objective.

Many computer simulation tools have been developed to simulate the overall building performance. Some of these tools are; EnergyPro, which is a comprehensive energy analysis program that performs several different energy calculations. EnergyPro is composed of an interface, which includes a building tree, a set of libraries, and a database of equipment directories. This software can produce room-by-room load calculation reports and HVAC psychometric diagrams (EnergPro, 2008). EnergyPlus is also a new generation of comprehensive energy analysis and thermal load simulation program. The BEANS Software is a comprehensive building simulation and analysis software developed by ARUP company. The energy simulation engines in BEANS combine thermal, lighting, solar radiation, air ventilation, and HVAC system simulation (BEANS, 2003). Solar-5 is an early generation of computer simulation, which provides data visualization of building performance (Solar-5, 2008). EnerWin building energy simulation software is a simple simulation model which is written in FORTRAN, and provides a base for integrating other simulation and optimization techniques to explore building performance. (Enerwin, 2008). TRNSYS software is an advanced simulation tool, which provides de-

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tailed simulation for building performance and tests the performance of the different parts of the HVAC system and passive design techniques (TRNSYS, 2008). These computer programs usually provide the designer with a relatively accurate and comprehensive performance of the selected design from an energy point of view, but do not provide designers with a clear picture of the potential energy saving by exploring other design alternatives.

In their effort to build a holistic evaluation tool of energy conservation in buildings, many researchers geared their efforts towards developing multi-aspects simulation and evaluation tools. Several comprehensive computer programs have been developed to create these evaluation and simulation tools. These are generally comprehensive and take into consideration a wide range of design variables, such as direct and indirect solar radiation, natural ventilation, building location and orientation, daylight, mechanical systems, thermal comfort parameters, activity patterns, as well as building regulations and cost.

One such tool is the knowledge-based computer-aided architectural design system, KB-CAAD. It is used for the schematic design and evaluation of passive solar buildings, introduced by Shaviv. This system is based on the integration of Knowledge-based and procedural simulation methods with the CAAD system for building representation. The knowledge base contains the heuristic rules for the design of passive solar buildings. Whenever possible, the knowledge base guides the designer through the decision-making process. However, if the rule of thumb is not acceptable for a particular design problem, the KB-CAAD system guides the architect by using a procedural simulation model. (Shaviv, 1990).

Another example of these tools is Building Design Advisor (BDA) developed by the Lawrence Berkley Lab. BDA is a Windows computer program that addresses the needs of building decision-makers from the initial schematic phases of building design through the detailed specification of building components and systems. The BDA is built around an object-oriented representation of the building and its context, which is mapped onto the corresponding representations of multiple tools and databases. It then acts as a data manager and process controller, automatically preparing input to simulation tools and integrating their output in ways that support multi-criterion decision making (BDA, 2000). However, this program provides the performance of each design solution in general, and does not investigate the potential contribution of each design element nor does it address the relationships among these elements in terms of energy saving.

ENERGY-10 software is another example of a tool developed to evaluate and advise designers on energy conservation. This software provides a quick way to automatically evaluate energy-efficient strategies revealing the individual effect of each building component on energy consumption. It also makes global modifications in building descriptions. These modifications are made based on the designer's selection.

Several simulation programs were also developed to predict the contribution of the different building components to energy consumption. For example, Malkawi introduced a simulation software that compares the simulated building performance to a "standard design", and provides a comparison between the two designs (Malkawi, 1994). Other software programs run multi-simulations for simple building geometries and derive an "optimum" building design from an energy conservation point of view (Al-Homoud, 1994). However, this software falls short of deriving the actual interaction between building design variables. Nor does it reveal the contribution of each of energy saving elements for specific buildings.

Another area of importance in building evaluation and optimisation is integrating building operation and control to the holistic building evaluation. Air-Conditioning control can reduce the total air-conditioning energy consumption in buildings by up to 47% if it is integrated with the other building design variables such as thermal mass (Mahdavi, 1995). Advances in air-conditioning system design and control strategies are among the major contributors to energy savings in existing buildings, which can reach up to 38% when compared to conventional approaches (Osman, 1996). This high saving potential has captured the attention of engineers. Related research topics include: development of a systems approach to optimal air-conditioning control, application of general regression neural networks in air-conditioning control, fuzzy logic and rough sets controller for air-conditioning systems (Yao, T. 1996), and finally, non-linear air-conditioning control (Zaheer, 1994). These studies introduced innovative solutions to control the air-conditioning systems and to improve the comfort level in buildings. However, none of these investigations integrated the impact of building components such as thermal mass, thermal insulation, solar radiation and natural ventilation on buildings' thermal performance in a holistic way.

Although both computer simulation programs and intelligent CAD systems contribute significantly to energy conservation, they cannot cover all design aspects, nor they can replace the rule of the designer. These computer simulation and optimization models usually target the design process from specific physical design aspects. The designer has a major role in evaluating the design from a holistic point of view and producing innovative techniques to conserve energy while considering other design aspects such as aesthetic, human needs, function, practical operating strategies, practical construction techniques, as well as the particular specifications of the owner. These expert systems usually provide suggestions or a single optimum solution based on a limited database as we discussed earlier which the designer may reject or accept. At the same time, the expert systems do not paint a clear picture of the contribution of each design element to energy conservation.

The goal of this research is to close this gap. The proposed model in this research will provide a range of potential energy saving of alternatives for each design elements. This model will establish the relationship between these design elements and energy saving in a form of mathematical equations and data visualization. Thus, the designer will continue to assume his rule as the ultimate decision maker, but on the light of clear information that shows the consequences of his decisions on the overall energy consumption of the building.

PROOF OF CONCEPT

The researcher believes that an ideal comprehensive evaluation model should include all the building design and construction aspects (Figure 1). However, some aspects such as aesthetic, social and cultural variables, and users' preferences are hard to be numerically measured. Therefore, the designer will continue to assume his/her role as the ultimate decision maker who will take all these aspects into account. This model will provide guidance that help the designer in making the right decisions on the light of the actual contribution of the design selections on energy consumption.

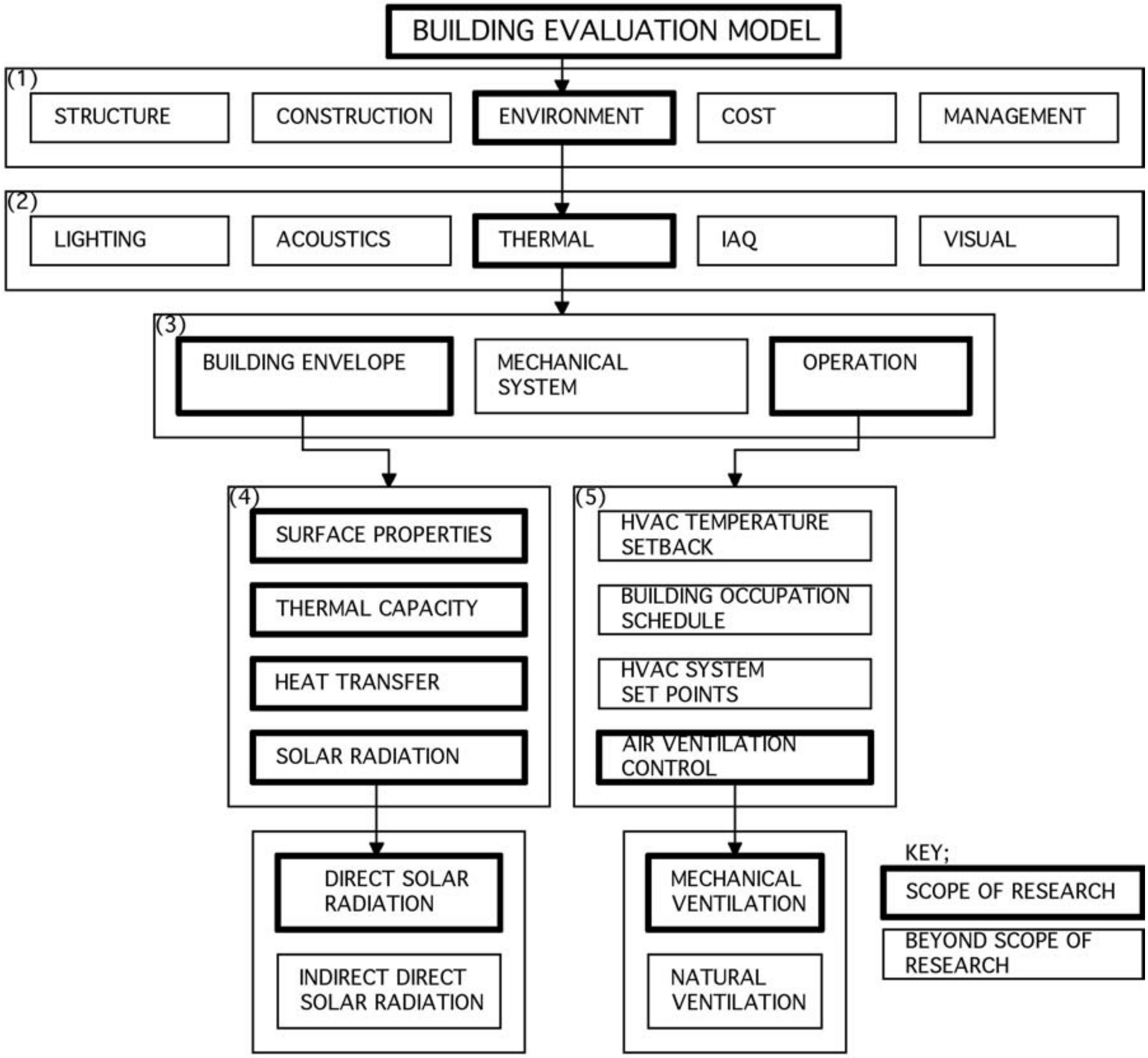
As a proof of concept, this research targeted main energy related design considerations that have major contributions to energy savings in buildings. These design considerations are shown in Figure 2. This research involves proposing a building evaluation model, which acts as a central agent between; A—Base Design Generator (Figure 2 (A)), and Alternative Design Analysis Tool that consists of; B—a solution generator, C—a simulation generator, and D—a data analysis and visualization tools (Figure 2 (B)). The evaluation model was used to recommend general design guidelines for using the thermal mass, thermal insulation, solar radiation, and natural ventilation (Figure 2(D)). In light of these recommendations, the research suggested new design and control strategies that include cooling by indirect night-time ventilation, cooling and dehumidification by direct ventilation, and dehumidification by direct ventilation through heat exchanger (Figure 2(C)).

Then the evaluation model was used again to test and validate these new ventilation strategies. Finally, the research recommended general ventilation design and control guidelines for similar buildings (Figure 2(E)).

A. Base design generator

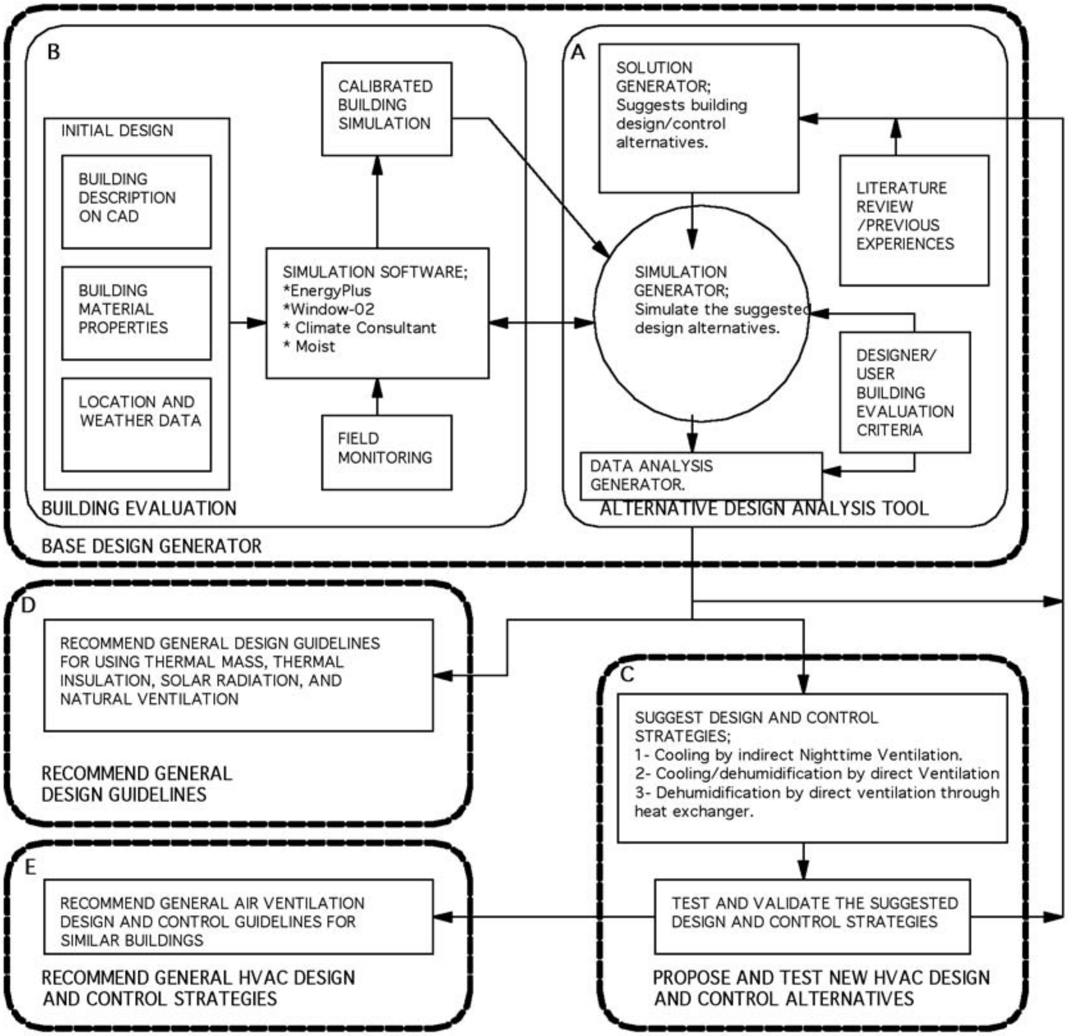
The base design generator will generate an initial design, and simulates it in energy simulation tools. Most variables in the base design input might have significant impact on the energy performance of the building. Since the scope of this research does not cover the initial conceptual design phase, the designer should have an initial idea of the contribution of the main building design elements to the energy consumption. For existing buildings, field monitoring will be used to calibrate the building simulation. These methodology is explained as follows; First, building parameters are described in EnergyPlus©, the building simulation software that is used for building simulation in this research, EnergyPlus was developed from both the BLAST and DOE–2 programs. BLAST (Energy-Plus, 2007). Energy Plus was selected in this research for the following reasons:

FIGURE 1. Overall Building Evaluation Framework. The highlighted components are the scope of this research.



- EnergyPlus integrates building and HVAC systems and perform simultaneous simulation where the building response and the primary and secondary HVAC systems are tightly coupled. It can also perform simulations on sub-hourly or user-definable time steps. This variable time steps improve the interactions between the thermal zones and the HVAC systems.
- EnergyPlus accepts ASCII text based weather, input, and output files that include hourly or sub-hourly environmental conditions. This feature is significant to build the evaluation model since multi-simulation is required.
- EnergyPlus performs a heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at interior and exterior surfaces during each time step.
- EnergyPlus performs transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions. It has also an improved ground heat transfer

FIGURE 2. Building evaluation structure overview.

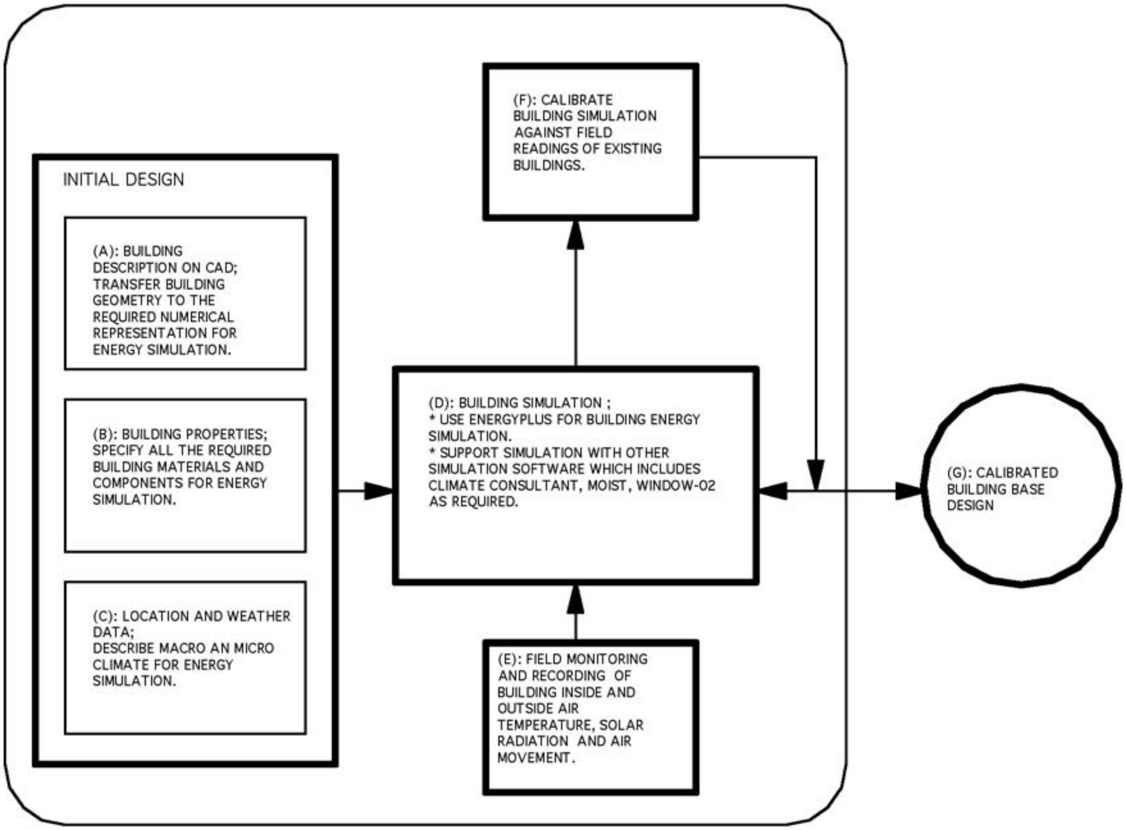


modeller that links to three-dimensional finite difference ground models and simplified analytical techniques. EnergyPlus also performs combined heat and mass transfer modeller that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD). This feature is significant in this research since both sensible and latent thermal storage are considered to balance the heating and cooling loads.

- EnergyPlus perform advanced fenestration calculations including controllable window blinds, electro-chromic glazing, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by windowpanes, and has a performance library for commercially available windows and shading.

Energy Plus requires initial building data, which includes location criteria, materials properties, mechanical system components, and thermal comfort

FIGURE 3. Base design generation.



parameters, Figure 3(A). EnergyPlus© also requires hourly weather data description, Figure 3(C). Then, Auto CAD is used to describe and transfer the building geometric description to a suitable file format, which can be input to EnergyPlus, Figure 3(B). Both the configuration and building components description comprise the initial building model.

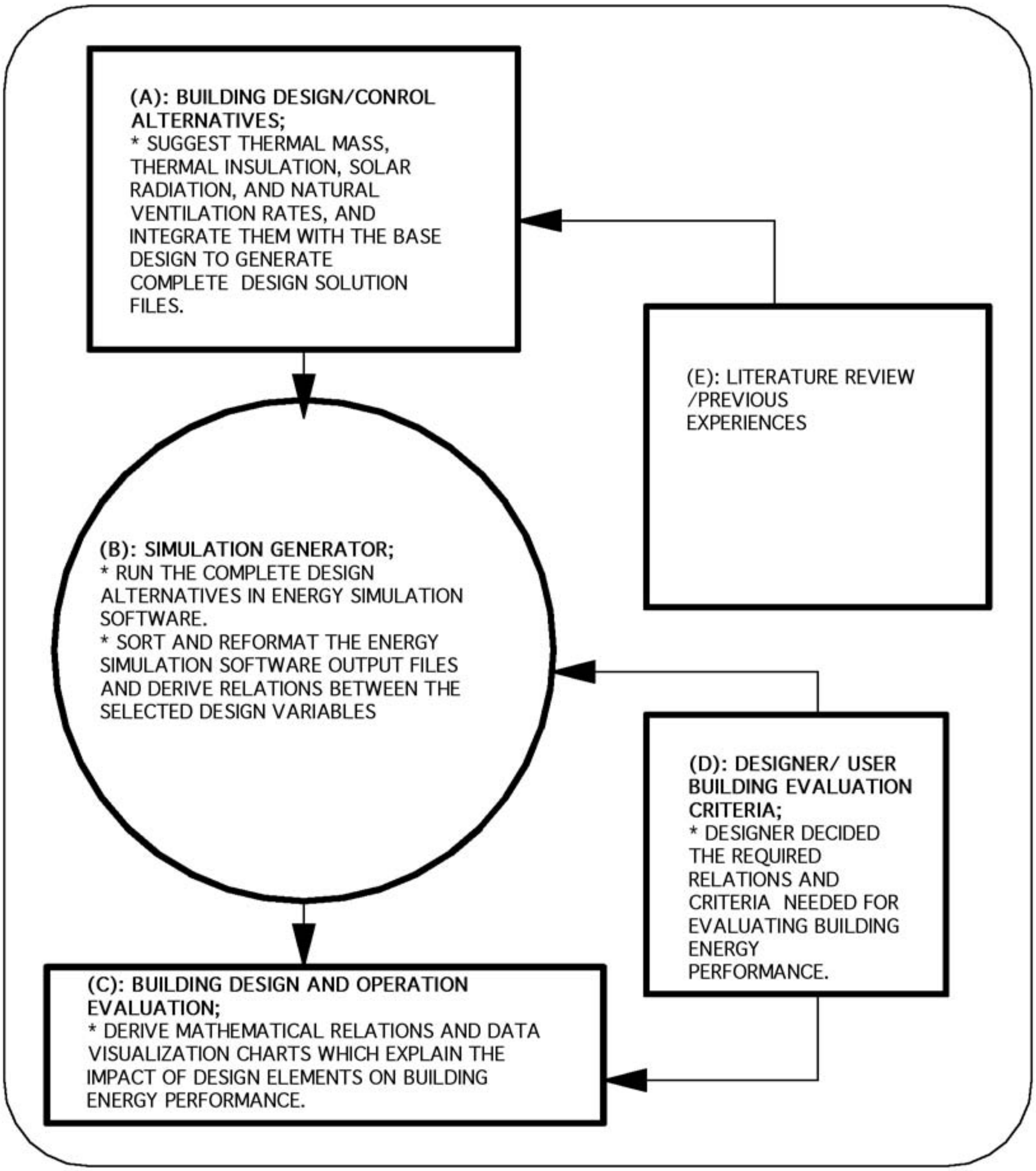
Calibrate the simulation results. Much research has been done in calibrating building energy simulation models. Carroll et al. (1993) introduced an iterative calibration method. Balcomb et al. (1994), proposed short term building monitoring and calibration. Wei et al. (1998) developed signatures showing the influence of different parameters on the heating and cooling energy consumption for use in calibration.

Since field data is available, Building monitoring was used in calibrating the simulation model. The initial simulation results were compared to the field readings, Figure 3(F). Under passive control, the building simulation was calibrated by matching the indoor air temperature with the field readings, and under active thermal control, the house simulation results were calibrated with the operation of the house air-conditioning as well as matching the indoor air temperature of the building with the field readings.

B. Alternative design analysis tool

After establishing the base design, the designer selects building components that will be tested, and then establishes a matrix of ranges of these building component alternatives such as a range of wall insulation thickness, window glass properties, roof and exterior walls solar radiation absorption, natural ventilation rates, or comfort level set points, Figure 4(A). The EnergyPlus© basic design file, and the alternative building component file are used to generate a matrix of complete input solutions to feed the simulation software. While establishing the ranges of building component values, the designer may take into consideration other design aspects such as aesthetics, cost, desired construction means and methods, and function. For example, if the designer would like to understand the consequences of increasing the glass area in the south façade of a building verses increasing the wall thickness to accommodate more thermal insulation. Then the designers will suggest a range of glass areas for the south façade and a range of insulation values for the exterior walls. The solution generator then generates a matrix of different variables of both the glass area and the wall insulation values that need to be tested.

FIGURE 4. Building simulation and analysis engines.



A simulation generator runs these design alternatives in EnergyPlus© and saves the results in appropriate file format, Figure 4(B). The solution generator accesses both the base design and the matrix of alternative solutions, assign one design alternative for each solution, and save the generated files in an appropriate format. The end product of this solution generator is a matrix of complete design solutions input files, which are passed to the EnergyPlus simulation software.

A Visual Basic© subroutine accesses the design alternatives and their associated simulation results which are obtained by EnergyPlus, and runs them in statistical analysis tools to extract mathematical relationships between the building component alternatives. These relations can also be exhibited in several charts, Figure 4(C).

C. Simulation generator

The simulation generator feeds EnergyPlus with the input files generated by the solution generator as discussed early. EnergyPlus run the required simulation engines and produces the required output. Since EnergyPlus can produce many output variables, the designer will select the output variables that will be considered in the design, as well as the type of analysis, relations, or data visualization of the output variables.

D. Statistical analysis and visualization

The designer can select the statistical analysis methods that explain the relationships between the building alternatives and its effect on the building thermal performance. The statistical analysis generator carries out statistical through analyses add in tools to Microsoft Excel 2003©. These analyses include the minimum, maximum, and average value, standard deviation, count, correlation analysis, linear and non-linear regression analysis, and ANOVA tables.

Data visualization is as important as mathematical relations when presenting the building thermal performance. The analysis generator can produce different types of charts, which show the relationships between the design variables and the associated heating and cooling load. These charts include X-Y scatter plots, smooth line plotting, area plotting, 3D charts, and bar charts.

The data visualization window helps the designer to visualize complex relations between the building design variables and help in taking the appropriate design decisions. Other advanced data visualization techniques such as multi dimensional data visualization can also be incorporated. The scope of this research is a proof of concept. This evaluation model hopefully will form the base for a comprehensive building evaluation methodology that will cover all the building design aspects.

IMPLEMENTATION

In order to test the proposed evaluation model, field study and computer simulations were conducted on an existing house in Virginia. The house area is approximately 480 m^2 and consists of a basement, first floor, and a partial second floor (Figure 9). The house designer has implemented several energy-conserving strategies such as passive solar radiation, thermal mass, thermal insulation, and air ventilation. The evaluation model was used to investigate the relationships between the main building design variables in this house, and their contribution to energy consumption in the house. These relationships were also used to predict the best ventilation strategies that reduce sensible and latent heating load. The details of this model testing are described as follows;

A. Generating alternative design solutions

A matrix of five different values of each of the above variables was used to generate design alternatives (Table 1). The solar radiation gain alternatives were achieved by setting the south windows glass shading control at 0-30W/m^2 The thermal insulation alternatives were achieved by setting the external walls U-values range between .23W/m^2 and 1.1W/m^2 and the thermal mass alternatives were achieved by setting the concrete floor slab thickness range between 0 and 6 inches.

Based on this matrix of alternative building components, the solution generator in the evaluation model generated 216 complete solution files in order to feed the simulation generator.

B. Building simulation

The simulation generator loaded the above design alternatives, runs them in the simulation engine, and saved the simulation output files. The statistical analysis engine loaded the simulation input and output files. Statistical analysis was conducted to examine the effect of the solar radiation, thermal

TABLE 1. Thermal mass, thermal insulation, and solar radiation design alternatives. Each set of thermal mass, thermal insulation, solar radiation represents a design alternative.

Matrix of alternative solutions used to derive relations between thermal mass, thermal insulation, solar radiation and building thermal load										
Glass Transmittance (%)	Exterior envelope U value (w/m^2)	Concrete Floor Thick (mm)		Glass Transmittance (%)	Exterior envelope U value (w/m^2)	Concrete Floor Thick (mm)		Glass Transmittance (%)	Exterior envelope U value (w/m^2)	Concrete Floor Thick (mm)
10	0.23	0								
10	0.5	0		20	0.23	0		20	0.5	0
10	0.9	76.2		30	0.23	76.2		30	0.9	0
10	1.3	114.3		40	0.23	114.3		40	1.3	0
10	1.7	152.4		50	0.23	152.4		50	1.7	0
20	0.23	0		10	0.5	0		10	0.23	38.11
20	0.5	0								
20	0.9	76.2		30	0.5	76.2		30	0.9	38.1
20	1.3	114.3		40	0.5	114.3		40	1.3	38.1
20	1.7	152.4		50	0.5	152.4		50	1.7	38.1
30	0.23	0		10	0.9	0		10	0.23	76.2
30	0.5	0		20	0.9	0		20	0.5	76.2
30	0.9	76.2								
30	1.3	114.3		40	0.9	114.3		40	1.3	76.2
30	1.7	152.4		50	0.9	152.4		50	1.7	76.2
40	0.23	0		10	1.3	0		10	0.23	114.3
40	0.5	0		20	1.3	0		20	0.5	114.3
40	0.9	76.2		30	1.3	76.2		30	0.9	114.3
40	1.3	114.3								
40	1.7	152.4		50	1.3	152.4		50	1.7	114.3
50	0.23	0		10	1.7	0		10	0.23	152.4
50	0.5	0		20	1.7	0		20	0.5	152.4
50	0.9	76.2		30	1.7	76.2		30	0.9	152.4
50	1.3	114.3		40	1.7	114.3		40	1.3	152.4
50	1.7	152.4								

mass, thermal insulation, natural ventilation, and the heating/cooling load of the house. A summary of the statistical analysis results were as follows:

C. Data analysis

A regression analysis was performed for the house to estimate the effect of four independent variables: 1) heat transmittance through the insulation (U), 2) the transmittance of the south-facing glass (ST), 3) the south zone concrete slab thickness in the first floor (TH), and 4) the ventilation air flow rate (VENT) on one dependant variable, cooling energy. The relationship may be estimated by the following expression:

Cooling Energy =
$$-6.7 + 6.22\,U + 21.7\,ST - 0.01\,TH - 0.4\,VENT \quad (1)$$

Where

Cooling Energy = the cooling energy (kw/h) which is needed to maintain the house within the comfort zone, and within a controlled air temperature of 18–26 C°

U = transmittance of insulation ($w/m^2.C°$)

ST = fraction of glass solar radiation transmittance

TH = concrete slab thickness which faces the south window (mm)

VENT = air ventilation rate transformation function which is $(X^2 - X)$ where X is the air ventilation rate (m^3/second)

The regression analysis result is presented in Table 2.

A regression analysis was also carried out between the average hourly solar radiation gain (SOL), heat transfer in building envelope (HT), and the building thermal mass (MASS) and thermal load is presented in the following relation:

Cooling Energy =
$$-3.9 + 1.22\,HT + .93\,SOL - 1.05\,MASS \quad (2)$$

Where

SOL = The total direct and indirect solar radiation (kW/h) admitted through the building envelop

H T = heat gain or loss through the building envelope (kW/h).

MASS = the overall internal mass of the building which is placed in the floor slab (ton/m^2 of concrete floor structure).

The regression analysis result is presented in Table 3.

The correlation coefficient between the hourly average solar radiation, the average heating gain/loss through the building envelop, and the thermal mass against the heating/cooling load of the building was 99.5, 99.2, 98 respectively. The relation between solar radiation and the heating load is presented in Figure 5. Figure 6 shows the relationship between envelope heat transfer and average heating load.

Figure 7 shows the effect of thermal mass, thermal insulation solar radiation on cooling load, and

TABLE 2. Regression analysis between cooling energy, insulation U value, glass transmittance, floor slab thickness, and air ventilation rate for equation (1).

Regression Statistics						
Multiple R	0.973763761					
R Square	0.948215862					
Adjusted R Square	0.933420394					
Standard Error	0.950468812					
Observations	19					
ANOVA						
	df	**SS**	**MS**	**F**	**Significance F**	
Regression	4	231.5870332	57.8967583	64.08826378	7.62657E-09	
Residual	14	12.64747347	0.903390962			
Total	18	244.2345067				
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	–6.71643213	1.386843548	–4.8429631	0.000260676	–9.690918357	–3.741945904
ST	21.73913584	2.977870635	7.30022842	3.9082E-06	15.35223286	28.12603882
TH	–0.019867073	0.005559612	–3.573463724	0.003055224	–0.031791266	–0.00794288
U	6.226219214	0.587763866	10.59306224	4.55507E-08	4.965589977	7.48684845
VENT	–0.400857525	0.172720267	–2.320848221	0.035901014	–0.771305985	–0.030409066

TABLE 3. Regression analysis between thermal load and thermal mass, thermal insulation and solar radiation for Equation (2).

Regression Statistics						
Multiple R	0.996867431					
R Square	0.993744674					
Adjusted R Square	0.992301138					
Standard Error	0.340753439					
Observations	17					
ANOVA						
	df	**SS**	**MS**	**F**	**Significance F**	
Regression	3	239.7997557	79.93325192	688.4097	1.43614E-14	
Residual	13	1.509467782	0.116112906			
Total	16	241.3092235				
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	–3.917309079	0.185095511	–21.1637173	1.86E-11	–4.317183543	–3.51743
load	1.228589075	0.058956523	20.83889973	2.26E-11	1.101221275	1.355957
sol	0.936086309	0.024708985	37.88445026	1.08E-14	0.882705803	0.989467
mass	1.052072115	0.069909772	15.04899926	1.33E-09	0.901041263	1.203103

FIGURE 5. The relation between the solar radiation gain and the heating load.

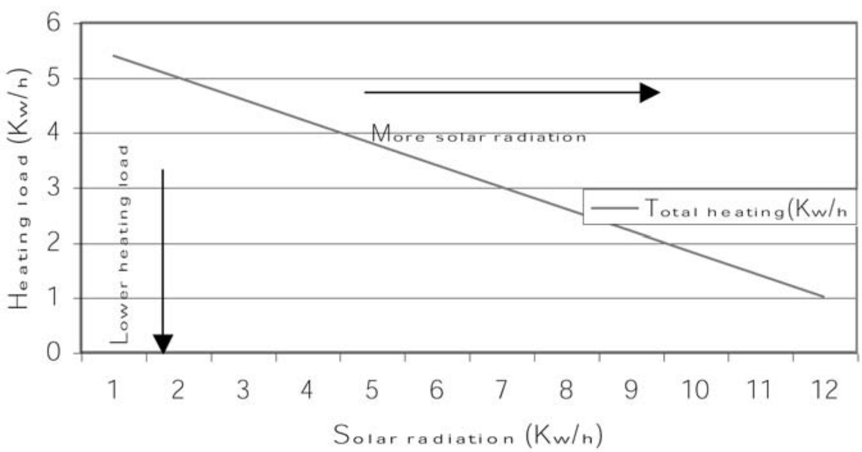


Figure 8 shows the thermal comfort levels which achieved by integrating thermal mass, thermal insulation, solar radiation, and natural ventilation.

CONCLUSION

There is no optimum and complete simulation, optimisation or evaluation model. It is clear that the energy simulation, optimisation, and evaluation models cannot make appropriate design decision on behalf of the designer. The designer only is capable of making these designs decisions. However, when designers are supported with appropriate evaluation tools that help in building a holistic picture of a particular design problem, designers can build strong

FIGURE 6. The relation between the thermal insulation and the heating load.

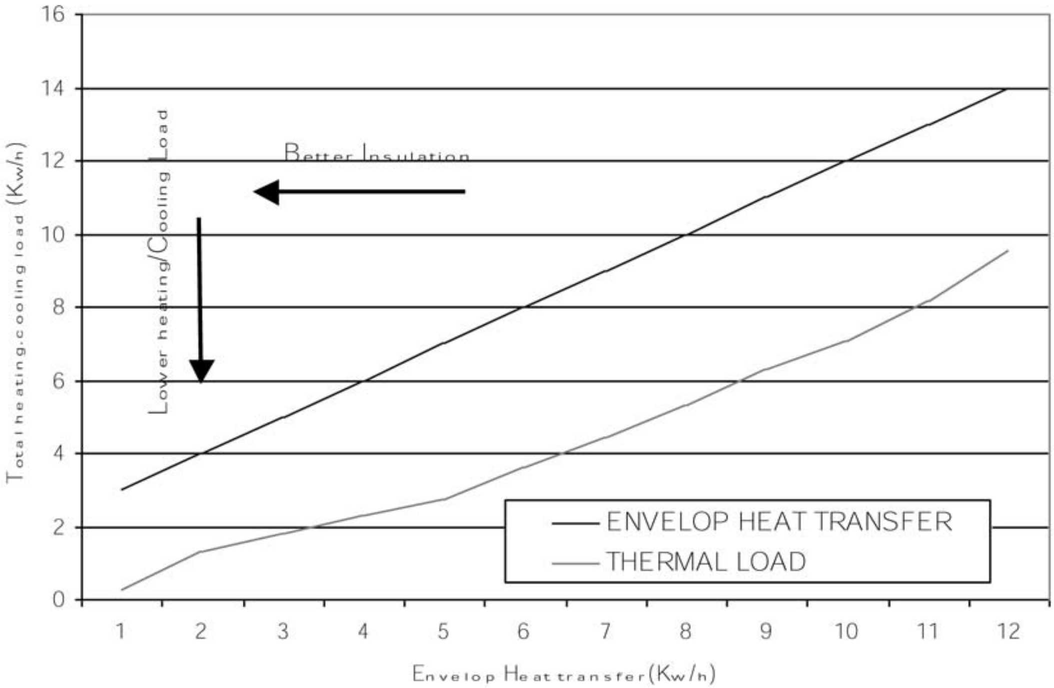


FIGURE 7. Effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on cooling load.

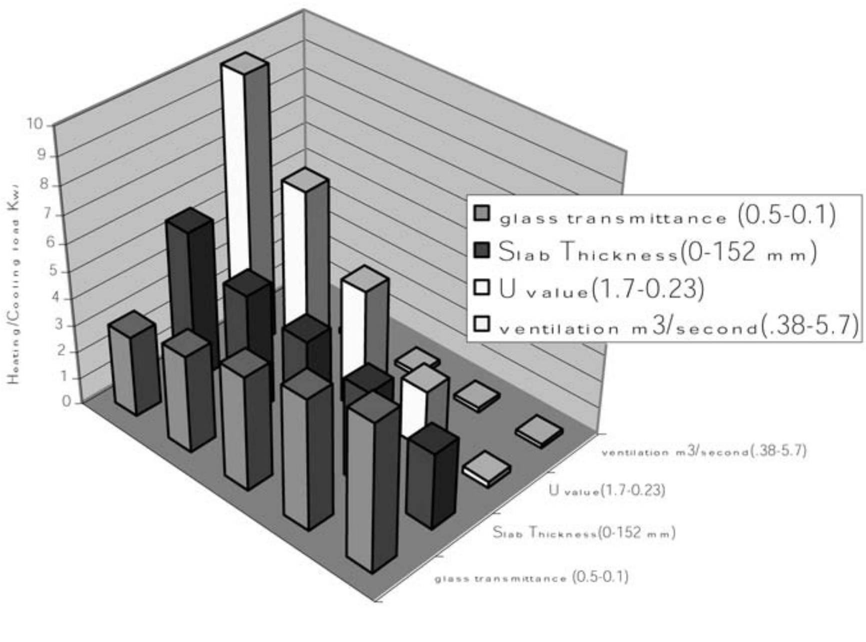
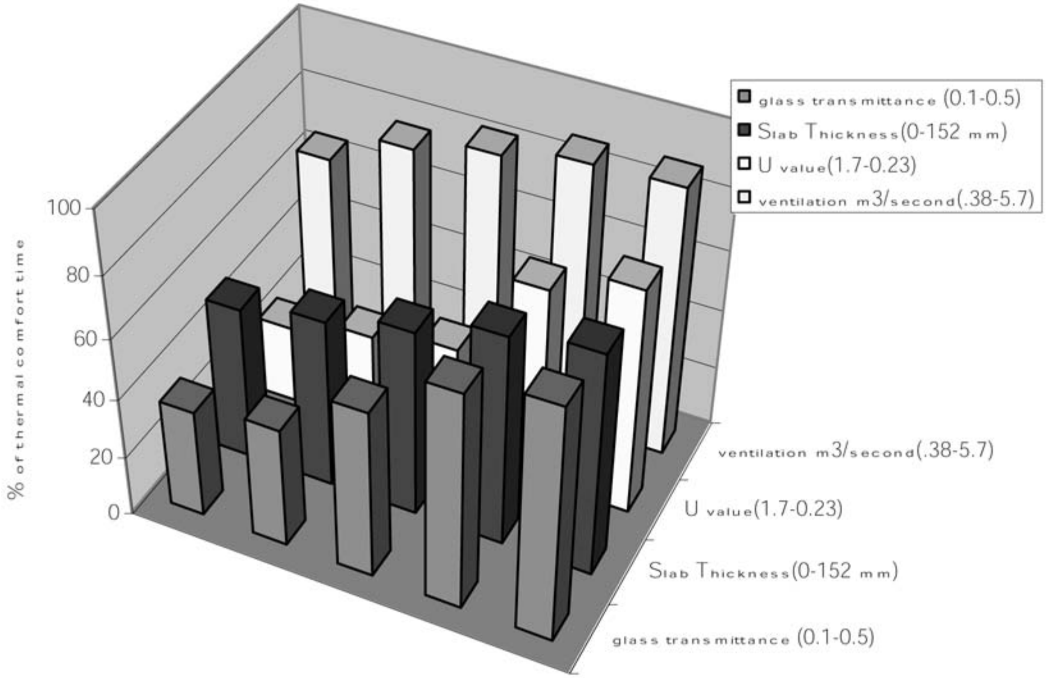


FIGURE 8. Effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on achieving passive thermal comfort.



intuitive feel and will be able to make more reasonable and accurate decisions.

Further more, rules of thumb and general design guidelines cannot supplement the required science and knowledge needed in order to produce appropriate architecture. Unlike the existing simulation and optimisation model which either simulate building's performance or suggest "optimum" solutions, this evaluation model provides comprehensive analysis and data presentation, which unveils the holistic picture of the integration and interaction between the main building components. The model also validates that many relations between building design variables and its effect on building energy performance, which have been derived in this research, could not have been obtained without the evaluation model exhaustive simulation and analysis.

This Evaluation model provides the designer with a clear picture of the effect of the design decisions on building energy performance. but also he/she will be able to predict the effect of the tradeoffs between these design variables on the building energy performance.

FIGURE 9. The Beliveau house south elevation.

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