THE DEVELOPMENT OF INTEGRATED BASED-SIMULATION DESIGN SUPPORT SYSTEM

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ABSTRACT

This paper explores effective means to opt for the optimum design solutions of commercial buildings through developing a Based-Simulation Design Support System (BSDSS). The system is established by the integration between EnergyPlus and Radiance software programs. The design alternatives of a typical private office are developed and evaluated based on multi-attribute life-cycle analysis. Results show that there is still a potential to improve the building design especially at the early stage.

KEYWORDS

Based-Simulation Design Support System (BSDSS); commercial buildings; life-cycle analysis; simulation programs; optimum design alternatives.

INTRODUCTION

With the recognition of climate change and depletion of conventional fuels, it is essential to consider energy efficiency as one of the main goals in building design due to the increasing demand and high cost of energy in the most industrialized countries. About 13% of the annual energy consumption in Canada and 12.5% of CO_2 emissions is due to the commercial and institutional sectors (Natural Resources Canada, 1997). Research activities in this field have typically concentrated on developing design solutions for existing case studies, leaving the preliminary design task to the architects. Conversely, architects and building designers endeavor to design buildings based on their experience, education and the rules-of-thumb, which lead to ineffective design concepts and unsubstantiated.

Limitations for optimizing systems and programs such as GenOpt (Wetter, 2004) are few proposed alternatives and objective functions (e.g. cost), approximations and the use of optimization techniques (e.g. response surface method) with error margins, which could lead to inaccurate results. Simulation programs such as EnergyPlus (2001) and Adeline (2000) used to calculate complex systems and models in design practice is often impeded by the fact that the operation of such programs is extremely complicated and time-consuming. In addition, they are predicting programs instead of optimizing tools. There is a need for a design tool to optimize the best available solutions and to accurately quantify the non-energy benefits. This paper presents the techniques and methods used to develop the Based-Simulation Design Support System (BSDSS).

THE DESIGN SUPPORT SYSTEM

The BSDSS is developed using C++ program and based on the integration between Radiance and EnergyPlus software programs. Thermal and visual models are developed first and then, the BSDSS automatically modify the design parameters of models according to information provided by users. A database is created including the entire simulation results, composing of a large number of design solutions. The alternatives include the variations of individual parameters and the available combinations between such parameters composing multi-dimensional groups. A selection tool, developed by Excel is used to derive the optimum alternatives via an interface section, which enables the user to input the information required for the analysis (e.g., life span of the building). Figure 1 illustrates the basic structure of the BSDSS.

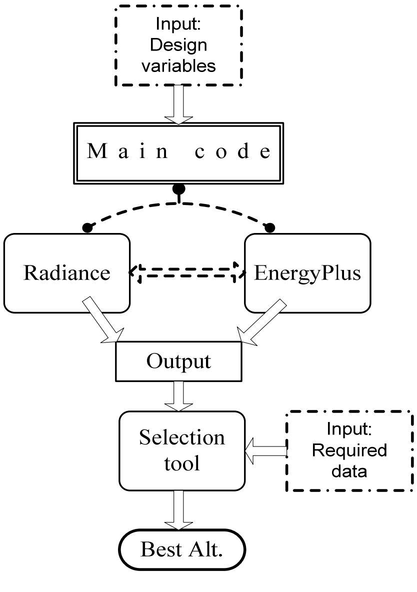

Figure 1. The basic structure of the BSDSS

One of the advantages of the BSDSS is that design alternatives can be assessed based on either thermal or visual, or on both thermal and visual performance. In this paper, only thermal performance of the base case and corresponding alternatives are presented.

The methodology (Kassab et al. 2002) used to build the selection tool of the BSDSS is based on the followings:

- Life-cycle energy including: the operating energy calculated by the EnergyPlus program.
- Life-cycle cost comprising: (i) the cost of building materials from Means Cost Data (2006); and (ii) the energy (heating + cooling + electricity) cost during the life-cycle of the building. For this simulation, we will use Alberta electricity rate and natural gas rate of \$0.0969/kWh and \$8.0/GJ, respectively. The present worth factor was used to calculate the present value of energy cost over the life cycle, assuming that the life span of the building is 30 years; interest rate including inflation is 7% and the energy escalation rate is 5%.
- The environmental impact is calculated in terms of equivalent CO_2 emissions by utilizing the Global Warming Potential (GWP) index (Masters, 1994) and pollutant calculations (Buhl, 1998). In Alberta, the coal and natural gas account for about 45% and 40% of electricity generation, respectively (Alberta Energy, 2004). The reset comes from other resources (e.g. wind), which is assumed not to generate greenhouse gases.

The Life-Cycle Analysis (LCA) approach was used to estimate the overall impact of such alternatives. For the selection of the best design alternatives based on the LCA approach, the normalized score (Tang et al. 1984) was used. Due to the difference in units of cost (\$), energy (kWh) and equivalent CO_2 emissions (kg), the normalized scale, from 0 to 1, was used for the life-cycle energy (N_{kWh}); life-cycle cost ($N_\$$); and equivalent CO_2 emissions (N_{co2}). For instance, the normalized scale of life-cycle cost ($N_\$$) is determined by:

$$N_\$ = (C_a - C_{min}) / (C_{max} - C_{min})$$

C_a is the life-cycle cost for alternative a (\$); and C_{min} and C_{max} are the minimum and maximum values of life-cycle cost (\$) with respect to all alternatives. Then the normalized score is established for each alternative by:

$$\text{Normalized score} = W_1 (N_\$) + W_2 (N_{kWh}) + W_3 (N_{co2})$$

W_1, W_2 and W_3 are weighting factors used for evaluating the impact of life-cycle energy use; life-cycle cost; and equivalent CO_2 emissions, respectively on the LCA of design alternatives. Figure 2 illustrates the hierarchy of the selection tool based on the life-cycle approach.

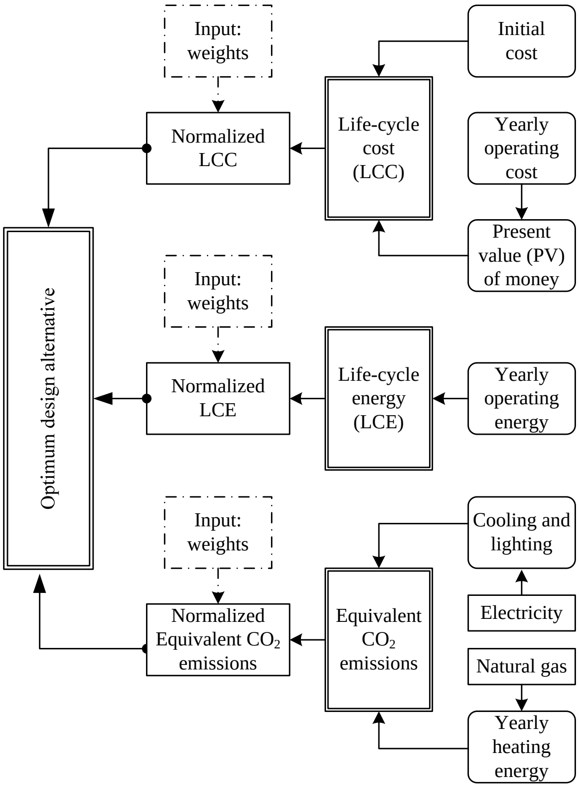

Figure 2. Hierarchy of the selection tool

Description of the Base Model

The Information and Communication Technology (ICT) is a rectangular office building, completed in 2001 at the University of Calgary. The building consists of seven floors with a total built-up area of approximately 17,000 m^2. It includes student spaces, corridors, and laboratories in the core and modular office spaces and service risers at the perimeter. Most of the offices face east and west.

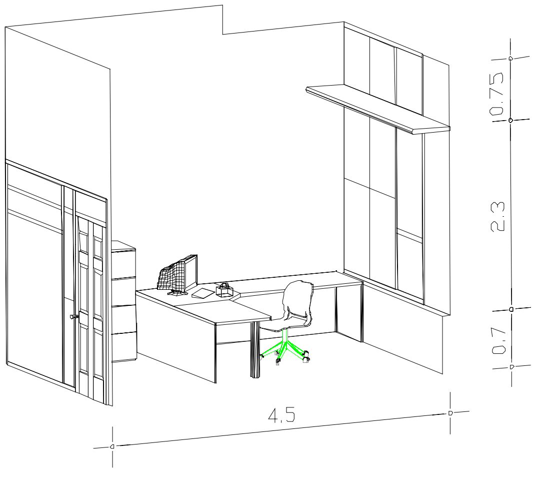

Figure 3. The typical office

In this research, a typical office (4.5 m by 2.9 m) facing east is used as a base model. The exterior façade is a curtain wall with a U-value of approximately 1.25 W/m^2.^{o}C. It is assumed that the electric lighting would be on during the working hours from 8:00 till 17:00. Figure 3 shows the office perspective.

The Generation of Design Alternatives

The parametric analysis of the base case showed that the design parameters that have significant impact on the building's thermal performance include: the thermal insulation of the spandrel panel (back pan), glazing area, glazing thermal properties, Solar Heat Gain Coefficient (SHGC) and the interior electric lighting. Several alternatives have been developed, as shown at Table 2. The thermal performance of the base case is evaluated according to the annual energy consumption including heating, cooling and electricity consumptions. The incremental costs of the selected parameters are assessed using Means catalogues (2006), whereas the (+) and (-) signs refer to the increase and reduction of the initial cost, respectively, with regard to that of the base case.

Table 1

Design parameters of the base model

Thermal insulation [m^2.^{o}C/W]	Glazing area [%]	Glazing U-value [W/m^2.^{o}C]	SHGC [--]	Lighting density [W/m^2]
2.03	52	1.5	0.46	13

Table 2

Design parameters and incremental costs of selected design alternatives

	Design Alternative values				
	Thermal insulation [m^2.^{o}C/W]				
	3.5	4.4	5.3	--	--
Incremental cost [$]	66	103	121	--	--
	Glazing area [%]				
	15	30	45	60	75
Incremental cost [$]	-929	-555	-181	193	568
	Glazing U-value [W/m^2.^{o}C]				
	0.9	1.2	1.8	2.1	2.5
Incremental cost [$]	440	180	-90	-150	-180
	SHGC [--]				
	0.2	0.3	0.6	--	--
Incremental cost [$]	0.0	0.0	0.0	--	--
	Lighting density [W/m^2]				
	8	10	15	17	19
Incremental cost [$]	96	78	-94	-106	-120

THE OPTIMIZATION OF OPTIMUM ALTERNATIVES

Simultaneous simulations and calculations are implemented to select the optimum design of the base case. A database of 3455 alternatives including the entire potential combinations is created. The information required for the life-cycle analysis via the selection tool is provided, as previously mentioned. Several weighting factors were proposed, as shown at Table 3 to illustrate the system's sensitivity and to optimise the optimum alternatives.

Table 3

Preferred weighting factors

	Weighting factor		
	Life-cycle energy	Life-cycle cost	*Equivalent CO_2 emissions*
Prefer_1	0.0	0.5	0.5
Prefer_2	0.5	0.0	0.5
Prefer_3	0.5	0.5	0.0

Subsequent to the implementation of the system, the database is automatically arranged from the best alternatives to the least attractive alternatives. Figures 4, 5 and 6 show the optimum 20 alternatives and their corresponding normalized scores.

For Prefer_1, results show that (see Figure 4) the impact of equivalent CO_2 emissions on the entire life-cycle (total) surplus that of the cost for the first 13 alternatives. This indicates that the environmental factor is the dominant feature of the life-cycle analysis when the weighting of energy is equal to zero. Furthermore, the environmental and energy aspects have approximately equal influences, whenever the weight of the life-cycle cost is 0.0 (see Figure 5). For Prefer_3 (Figure 6), the life-cycle energy is the foremost factor in determining the optimum design solutions, whenever the equivalent CO_2 emissions are equal to zero.

Tables 3, 4 and 5 present the optimum design alternatives for Prefer_1, Prefer_2 and Prefer_3, respectively. The values, described for each alternative are only the modified parameter values with respect to that of the base case. For instance, the design parameters for Alt1: insulation conductivity, glazing area, glazing U-value, SHGC, and lighting density would be equal to: 0.028 m.^{o}C/W, 0.15, 1.5 W/m^2.^{o}C, 0.6, and 13 W/m^2, respectively. It is noted that the combination between the parameter of glazing area (0.15) and SHGC of 0.6 has a great impact in determining the best alternatives. This is a result of the considerable reduction of initial cost ($929). The increase of SHGC from 0.46 to 0.6 would compensate the solar related heat loss due to the reduction of glazing area.

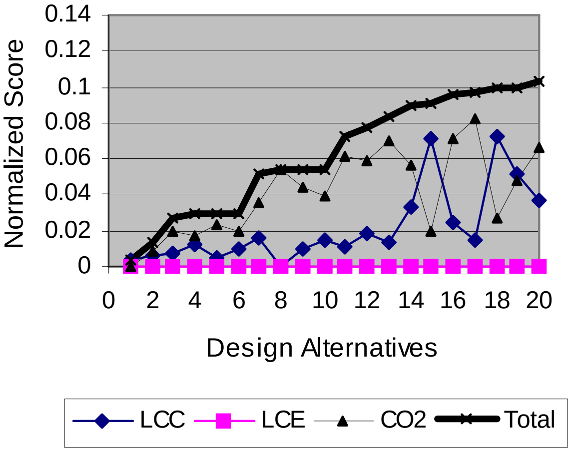

Figure 4. Optimum alternatives for LCE=0, LCC=0.5 and equivalent CO_2 emissions=0.5

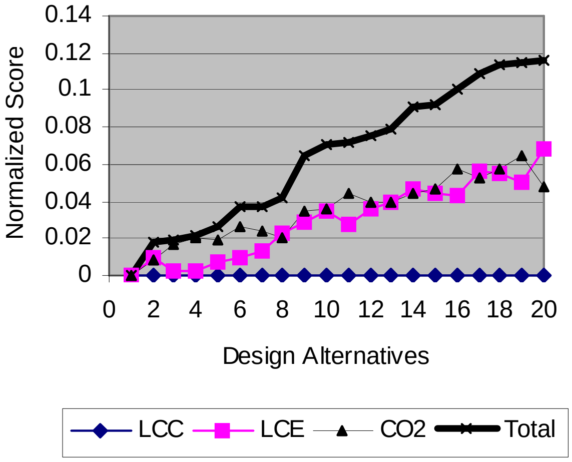

Figure 5. Optimum alternatives for LCE=0.5, LCC=0.0 and equivalent CO_2 emissions=0.5

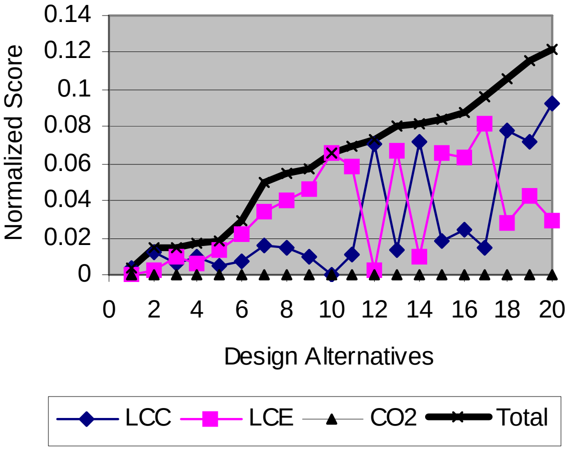

Figure 6. Optimum alternatives for LCE=0.5, LCC=0.5 and equivalent CO_2 emissions=0.0

Table 3
Optimum design parameters for Prefer_1

Design alternatives A1	Life-cycle energy [kWh]	Life-cycle cost [$]	Equivalent CO_2 emissions [ton]
Alt1: Insulation conductivity& Glazing area & SHGC are: 0.028 & 0.15 & 0.6			
	42.7	1194.3	13.8
Alt2: Insulation conductivity& Glazing area & SHGC are: 0.034 & 0.15 & 0.6			
	43.8	1211.2	14.1
Alt3: Insulation conductivity& Glazing area & SHGC are: 0.043 & 0.15 & 0.6			
	45.5	1222.5	14.6
Alt4: Insulation conductivity& Glazing area & Lighting density are: 0.028 & 0.15 & 248			
	42.9	1264.3	14.4
Alt5: Insulation conductivity& Glazing area & Lighting density are: 0.043 & 0.15 & 248			
	44.3	1210.2	14.7
Alt6: Insulation conductivity& Glazing area & Lighting density are: 0.034 & 0.15 & 248			
	43.5	1247.0	14.5
Alt7: Insulation conductivity& Glazing area & Glazing U-value & SHGC are: 0.028 & 0.15 & 1.8 & 0.6			
	47.0	1297.4	15.2
Alt8: Glazing area & Glazing U-value & SHGC are: 0.15 & 1.8 & 0.6			
	51.0	1165.2	15.8
Alt9: Insulation conductivity& Glazing area & Glazing U-value & SHGC are: 0.043 & 0.15 & 1.8 & 0.6			
	48.6	1246.9	15.5
Alt10: Insulation conductivity& Glazing area & Glazing U-value & SHGC are: 0.034 & 0.15 & 1.8 & 0.6			
	47.7	1286.2	15.3

Table 4
Optimum design parameters for Prefer_2

Design alternatives A2	Life-cycle energy [kWh]	Life-cycle cost [$]	Equivalent CO_2 emissions [ton]
Alt1: Insulation conductivity& Glazing area & SHGC are: 0.028 & 0.15 & 0.6			
	42.7	1194.3	13.8
Alt2: Insulation conductivity& Glazing area & SHGC are: 0.034 & 0.15 & 0.6			
	43.8	1211.2	14.1
Alt3: Insulation conductivity& Glazing area & Lighting density are: 0.028 & 0.15 & 248			
	42.9	1264.3	14.4
Alt4: Insulation conductivity& Glazing area & Glazing U-value & Lighting density are: 0.028 & 0.15 & 0.9 & 222			
	42.9	1752.6	14.5
Alt5: Insulation conductivity& Glazing area & Lighting density are: 0.034 & 0.15 & 248			
	43.5	1247.0	14.5

Table 5
Optimum design parameters for Prefer_3

Design alternatives A3	Life-cycle energy [kWh]	Life-cycle cost [$]	Equivalent CO_2 emissions [ton]
Alt1: Insulation conductivity& Glazing area & SHGC are: 0.028 & 0.15 & 0.6			
	42.7	1194.3	13.8
Alt2: Insulation conductivity& Glazing area & Lighting density are: 0.028 & 0.15 & 248			
	42.9	1264.3	14.4
Alt3: Insulation conductivity& Glazing area & SHGC are: 0.034 & 0.15 & 0.6			
	43.8	1211.2	14.1
Alt4: Insulation conductivity& Glazing area & Lighting density are: 0.034 & 0.15 & 248			
	43.5	1247.0	14.5
Alt5: Insulation conductivity& Glazing area & Lighting density are: 0.043 & 0.15 & 248			
	44.3	1210.2	14.7

Modifications of the Proposed Design Parameters

To further examine the influence of glazing area on the life cycle of the base case, the glazing areas of 15% and 30% have been removed from the proposed alternatives. Hence, the remaining alternatives for this parameter would include the values of: 45%, 60% and 75% (see Table 2). Figure 7 illustrates the optimum alternatives and their corresponding normalized scores. Equal weighting factors of 0.33 were proposed for the life-cycle energy, life-cycle cost, and equivalent CO_2 emissions. Results show that the life-cycle cost has the most significant impact on the entire life cycle, compared with that of the life-cycle energy and equivalent CO_2 emissions. Furthermore, the reduction of glazing area still has the foremost impact on establishing the best alternatives (Table 6).

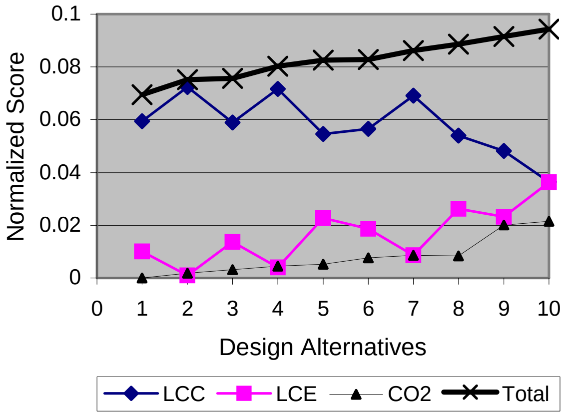

Figure 7. *Optimum alternatives for LCE=0.33, LCC=0.33 and equivalent CO_2 emissions=0.33*

Table 6
Optimum design parameters for the modified model

Design alternatives	Life-cycle energy [kWh]	Life-cycle cost [$]	Equivalent CO_2 emissions [ton]
Alt1: Glazing area& Insulation conductivity& Glazing U-value& SHGC& Lighting density are: 0.45 & 0.028 & 0.9 & 0.3 & 104			
	53.0	3034.9	17.4
Alt2: Glazing area& Insulation conductivity& Glazing U-value& Lighting density are: 0.45 & 0.028 & 0.9 & 104			
	51.5	3142.9	17.4
Alt3: Glazing area& Insulation conductivity& Glazing U-value& SHGC& Lighting density are: 0.45 & 0.034 & 0.9 & 0.3 & 104			
	53.6	3030.5	17.5
Alt4: Glazing area& Insulation conductivity& Glazing U-value& Lighting density are: 0.45 & 0.034 & 0.9 & 104			
	52.0	3136.7	17.6
Alt5: Glazing area& Insulation conductivity& Glazing U-value& SHGC& Lighting density are: 0.45 & 0.028 & 0.9 & 0.2 & 104			
	55.1	2994.4	17.6

DISCUSSIONS AND CONCLUSIONS

The integrated Based-Simulation Design Support System (BSDSS) is a step forward to overcome the limitations of decision-making systems. The major deficiency of the BSDSS is time consuming. For instance, 75 hours is required to develop a group of 3455 alternatives, using a Pentium 4 computer. In the future, less time is expected as a result of evolving computer technologies, co-processors and refinement of the program. On the other hand, one of the advantages of the BSDSS is to consider the user's preferences, expressed in the weighting factors.

For the first 10 attractive alternatives (Figure 7), results show that the life-cycle cost is the major factor in establishing the optimum alternatives, when equal weighting scores are used. The life-cycle energy is thus the prevailing feature, when the environmental impact (CO_2 emissions) is neglected (Figure 6), while the environmental impact is considered the main factor when the preference of the life-cycle energy is close to zero (Figure 4). The environmental and energy aspects have equal influences (Figure 5), whenever the weight of the life-cycle cost is equal to zero. Results from Tables 3 to 6 show that the glazing area is the foremost design parameter, especially if combined with higher values of SHGC. These parameters should be considered precisely in building design. Future work is required to integrate the visual and thermal models together within the BSDSS.

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