Improving the Energy Performance of Houses in Montreal Using the Life-Cycle Analysis

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ABSTRACT

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This study presents tools to select the optimum solutions recommended for the design of energy-efficient house in Montreal, Canada. The computer model of the base case house was developed using BLAST program and using on-site measurements such as air leakage based on blower door test, short-term monitoring of indoor air temperature and electricity consumption derived from utility bills. Several design alternatives have been developed using both parametric and non-parametric approaches.

The developed design alternatives included: (i) the modifications of the characteristics of building envelope, (ii) the modifications of the architectural design and (iii) the building operating conditions. The energy performance of selected design alternatives was evaluated using the calibrated model of base case and BLAST program. Results show that although the base case house is already energy efficient, there is still potential to improve its energy performance via developing the design tools of the house.

The concept of energy efficiency includes more than the total energy consumption. The performance of the selected alternatives has been evaluated by using the multi-attribute life-cycle analysis. Three objective functions were used in the life-cycle analysis: (1) the total energy consumption, including the embodied energy and the operating energy; (2) the life-cycle cost, including the initial and the energy operating costs and (3) the environmental impacts, evaluated by using the Global Warming Potential (GWP) index, which is calculated in terms of equivalent CO_2 emissions.

A database of design alternatives and related life-cycle performance has been developed in this study. A Decision Support System based on previous database for evaluating the design alternatives has been established to select the best set of alternatives during the energy-efficient design of low-residential buildings in Canada.

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LIST OF PARAMETERS AND ACRONYMS

Φ_j	the Conduction Transfer Function coefficient, where $j = 0,1,\ldots nz$ [W/m²·°C]
δ	time interval [hour]
A	gross wall area [m²]
a	the effective interest rate
C	flow coefficient [L/(s·Pa^n)]
C_a	the value of life-cycle cost for alternative a [\$]
C_j	the annual heating cost for alternative j in the first year [\$]
C_{max}	the maximum value of the life-cycle cost with respect to all alternatives [\$]
C_{min}	the minimum value of the life-cycle cost with respect to all alternatives [\$]
DD	heating degree days for the location [°C]
e	the rate at which energy costs are expected to increase (including inflation)
g	log (C)
h_{ci}	convection coefficient of the inside surface face [W/m²·°C]
h_{co}	convection coefficient of the outside surface face [W/m²·°C]
i	the discount rate or cost of money including inflation
n	flow exponent
n''	planning horizon
N_S	normalized value for the life-cycle cost of alternative a
PW_j	present worth value for alternative j [\$]
ΔP	pressure difference between the outside and inside of the house [Pa]
q_{asol}	absorbed direct and diffuse solar radiation flux [W/m²]

$\dot{q}_{CE}$	convection of the internal loads [W]
q_{ci}	convective heat flux to zone air [W/m^2]
q_{co}	convective flux with outside air [W/m^2]
$\dot{q}_{conv}$	convective heat transfer from surfaces to the zone air [W]
$\dot{q}_{IV}$	sensible load due to infiltration and ventilation air [W]
q_{ki}	conductive heat flux at inside face of the wall [W/m^2]
q_{ko}	conductive heat flux at outside face of the wall [W/m^2]
q_{sol}	transmitted solar radiation flux absorbed at surface [W/m^2]
q_{SW}	net shortwave radiant flux from lights to surface [W/m^2]
q_{LWR}	net longwave radiation flux exchanged with surroundings [W/m^2]
q_{LWS}	longwave radiation flux from equipments in the zone [W/m^2]
q_{LWX}	net longwave radiant exchange flux between zone surfaces [W/m^2]
$\dot{q}_{sys}$	heat supplied or extracted from the zone by the HVAC system [W]
Q	air flow rate [L/s]
Q_{50}	air flow rate at 50 Pa [L/s]
Q_s	space heating energy consumption target [kWh]
Q_w	domestic hot water energy consumption target [kWh]
S	1.25 for fuel-fired space heating system, or 1.0 for electric heating system [kWh]
SHGC	solar heat gain coefficient
T_a	the zone air temperature [°C]
T_{cont}	the required air temperature set by the control profile [°C]
T_i	inside face temperature [°C]

T_o	outside face temperature [^{o}C]
$T_{si_{i,j}}$	inside face temperature [^{o}C] for surface i = 1, 2, … 6 and time j = 1, 2,…24
$T_{so_{i,j}}$	outside face temperature [^{o}C] for surface i = 1, 2, … 6 and time j = 1, 2,…24
T_w	cold water supply [^{o}C]
$Th_{average}$	average thermal resistance of the opaque wall [m^2·^{o}C/W]
Th_B	thermal resistance of the exterior wall (Detail B, Figure 3.6) [m^2·^{o}C/W], with area A_B [m^2]
Th_C	thermal resistance of the exterior wall (Detail C, Figure 3.6) [m^2·^{o}C/W], with area A_C [m^2]
Th_D	thermal resistance for floor and wall connection (Detail D, Figure 3.7) [m^2·^{o}C/W], with area A_D [m^2]
Th_{ST}	thermal resistance of the exterior wall through wood studs [m^2·^{o}C/W], with area A_{ST} [m^2]
V	interior heated volume including basement [m^3]
V_{house}	the volume of the house [m^3]
W	1.72 for fuel-fired systems, or 1.075 for electric systems [kWh]
W_1, W_2, W_3	weighting factors used for evaluating the overall impact of design alternatives
X	log (ΔP)
Y	log (Q)
X_j; Y_j; Z_j	the Conduction Transfer Function coefficient, where j = 0,1,…nz [W/m^2·^{o}C]

CHAPTER 1

INTRODUCTION

1.1 General

Nowadays, there is an increasing demand of energy in the most industrialized countries, and it is expected that the demand on energy will double in the next two decades. About 20% of the annual energy consumption in the industrialized countries including Canada is due to the residential sector (Hickling Corporation, 1993). Because of energy increasing costs, depletion of resources of fossil fuels and global warming due to greenhouse gases emissions, it is vital to consider energy efficiency as a major goal of our buildings design.

Although many studies and research work have established the area of energy efficiency in last decades, most of these worked on improving the thermal performance of conventional houses. The techniques, used to improve the thermal performance of houses, aimed mainly on increasing the thermal resistance and airtightness of the building envelope along with improving the performance of the mechanical and ventilation systems. There is a little information about the impact of architectural design (e.g. orientation, glazing-to-wall ratio, building form, etc.) on the energy performance of buildings. This thesis provides tools to support the energy-efficient design and to diagnose life-cycle performance of these tools, in order to improve the energy efficiency of low-residential buildings in Canada.

1.2 Scope and Objective

The scope of this study is to provide tools for selecting the best solutions for the energy-efficient design of a sustainable house in Montreal, Canada. The design of the base case house has been improved by developing the design alternatives of the materials characteristics of building envelope, and the architectural design. Other aspects such as improving the design of mechanical and ventilation systems are not included. The core of this work is analyzing the impact of the relevant design alternatives on the energy performance of the base case house to select the best alternatives for the energy-efficient design of new houses.

The objective is to develop a methodology to improve the energy performance of low-residential buildings in Canada. The sub-objectives are: (i) to develop several design alternatives, using both parametric and non-parametric approaches and to quantify the impact of such alternatives on the energy performance of the base case house, (ii) to evaluate the performance of design alternatives, using multi-attribute life-cycle analysis including the total energy consumption, the total cost, and the environmental impacts, calculated in terms of equivalent CO_2 emissions, and (iii) to develop a decision support system based on the evaluation of the selected design alternatives to support the decision making of building designers.

1.3 Approach

The methodology used in this research is as follows:

- Literature review of similar researches and projects including life cycle analysis, simulation computer programs, technical methods and techniques (chapter 2).

- Analysis of the prototype house, which is used as a base case, from the point of view of energy efficiency and the life cycle of the building. The advanced simulation program BLAST is used to establish the computer model of the base case (chapter 3).

- Monitoring of the base case house "Ray-Vision House" built in Montreal, Quebec to diagnose the thermal performance of the real scale project by using on-site measurements such as air leakage based on the blower door test, short-term monitoring of indoor air temperature and electricity consumption (chapter 4).

- Calibration of the computer model of the base case by comparing the simulation results and monitoring results of the real project to enhance the accuracy of computer model (chapter 4).

- Development of several design alternatives, including: (i) the modifications of the characteristics of building envelope; (ii) the modifications of the architectural design; and (iii) the building operating conditions (chapter 5).

- Establishment of the computer models of design alternatives by modifying the calibrated computer model of the base case according to the actual modifications of the alternatives. The evaluation of the energy performance of the relevant design alternatives is performed by comparing the energy consumption results with that of the base case house (chapter 5).

- Analysis the life cycle performance of each design alternatives, including three objective functions: (i) the total energy consumption, including the initial or embodied energy and the operating energy; (ii) the life-cycle cost, including the initial or investment cost and the energy operating costs and (iii) the environmental impacts, evaluated by using the Global Warming Potential (GWP) index, which is calculated in terms of equivalent CO_2 emissions. A database of design alternatives and related life-cycle performance has been developed (chapter 6).

- A decision support system based on the previous database is proposed to select the best set of for the energy-efficient design of low-residential buildings (chapter 6).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There is increasing demand from both the public and private sectors to establish innovative techniques and procedures to improve the thermal performance of residential buildings. Last decade, considerable efforts were made to reduce the energy consumption of buildings by modifying the traditional building design and construction materials.

In this chapter, the recent work carried out in this field is introduced, focusing on the energy performance of low-residential buildings in Canada. Two of the major approaches used to evaluate and upgrade the thermal performance of residential buildings are presented: (i) the engineering approach including the scientific basics, used by scientists and engineers to improve buildings performance and (ii) the architectural approach, which illustrates the rules of thumb and empirical knowledge implemented by architects and building designers. Advanced programs for energy-efficient design, established in the last decades are presented.

2.2 Engineering approach

The engineering or "scientific" approach is used by building engineers to improve the thermal performance of buildings using a knowledge base, developed with experiments, theoretical studies and monitoring.

The engineers aimed to improve the energy performance of buildings through: (i) improving the thermal performance to reduce the operating energy consumption of buildings, and (ii) reducing the embodied energy of the construction materials. The upgrading techniques and guidelines used by researchers are presented in this section.

2.2.1 Energy performance of residential buildings

The energy performance of buildings are classified in two categories (Prahl, F. 1998): (i) the heating and cooling consumption, and (ii) the base load including the consumption of the domestic hot water, cooking, lighting and electrical appliances. In cold climate countries such as Canada, the heating consumption has a high contribution to the energy consumption. In monitoring of 115 homes in Montreal (Zmeureanu, R. 1995), the heating was found to contribute 60% to 80% of the total energy consumption whereas the domestic hot water was responsible for 15% to 25% and the rest consumption was for lighting and appliances. The average annual energy consumption was in the range of 215 to 240 KWh/m^2·yr. Reducing the energy consumption via improving the thermal performance of building envelope was the concern of many researchers in Canada.

Description of building enclosure components

The term of building enclosure refers to the outside building assembly that encloses the entire building conditioned spaces and through which thermal energy is transferred to or from the outdoor environment. Building enclosure includes the external walls of the basement, above ground walls, windows, slab-on-grade, and the roof. Figure 2.1 illustrates the building enclosure assembly of a conventional house in Canada.

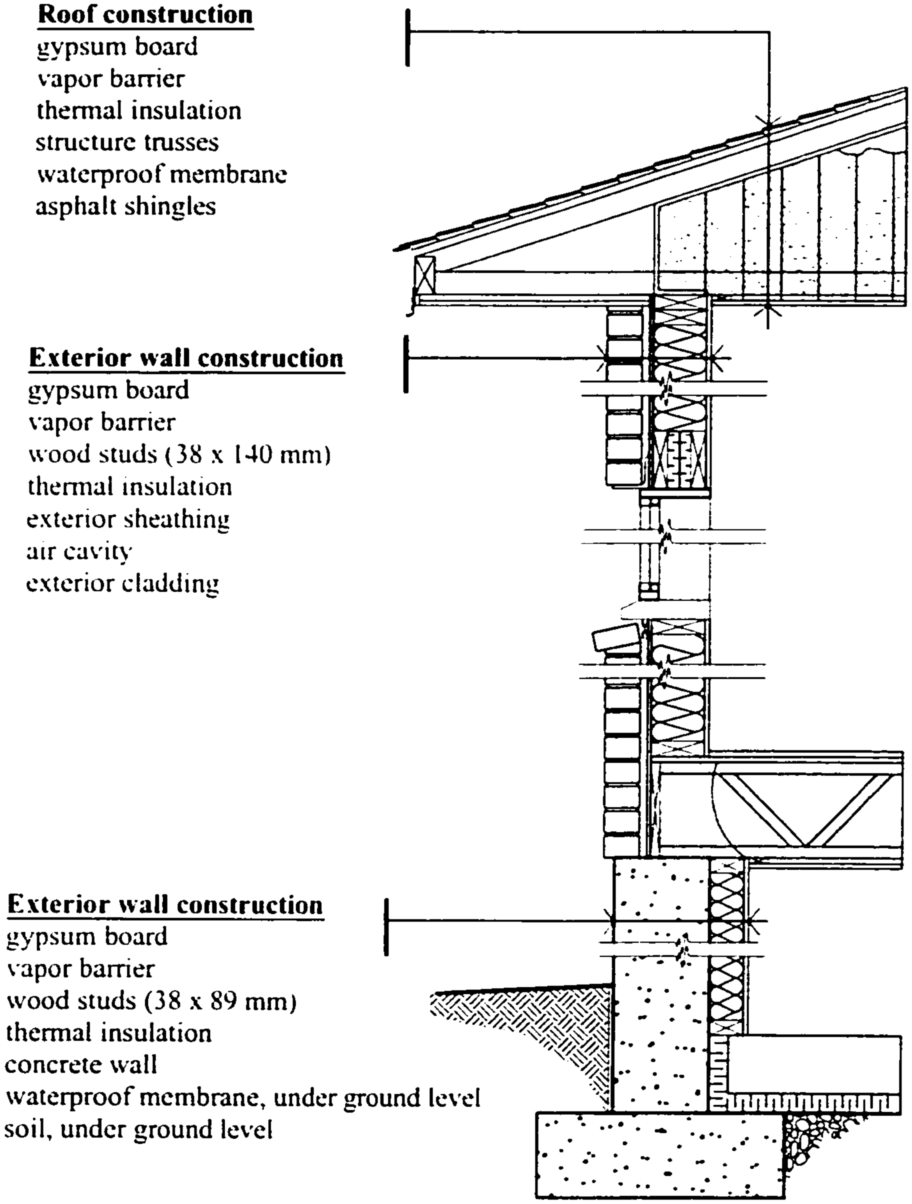


Figure 2.1. Assembly of building enclosure for a conventional house in Canada

The purpose of building enclosure is to control heat flow, rain penetration, light and noise and to provide the strength and rigidity to the building to withstand the external and internal forces, e.g. wind forces and earthquakes. Most of the thermal performance problems of building envelope are: (i) heat transfer through the assembly because of conduction, convention and radiation; (ii) air movement (infiltration) through the envelope as a result of pressure difference on the both sides of the assembly; and sometimes (iii) moisture accumulation as a result of rain penetration and/or vapor condensation in the building envelope.

For a typical building, the energy lost through exterior windows accounts for about 53% of the entire energy loss from the building envelope (Keith, E., 2002), while 27% is lost due to the outside air (infiltration) and approximately 20% is lost through the opaque elements such as the walls. Therefore, more consideration has been given to the thermal insulation, continuous vapor and air barrier and double-glazing windows in recent residential buildings in Canada.

Upgrading techniques and case studies

The following case studies are selected from literature and presented in this section. In the evaluation of energy performance of nine identical row houses in Montreal, Canada (Zmeureanu *et al.* 1998), major complains were regarding to the cold floors, cold drafts, condensation on windows and the non-uniform heating conditions. The problems were found to result from voids in the thermal insulation of exterior walls and roof, degradation of the seal gasket of the windows and heat losses from the ducting system.

The average air infiltration rate at 50 Pa was 5.8±0.9 ach, and the normalized energy consumption of houses was 123.7±24.7 kWh/m^2, while the heating consumption represented 57±14% of total electric energy consumption. Recommendations, established to improve the thermal performance of houses, included reducing the air infiltration through caulking around external openings, weather-stripping and installing foam gasket in electric outlets. The predicted savings were about 31% of annual heating cost. By balancing the heat recovery and reducing the thermostat setpoint, the estimated reduction of annual heating cost was 24% and 13% respectively.

In his study of refurbishment of two-story house in Saskatchewan, Canada, Dumont (2000) replaced the old exterior walls and roof by a hyper insulated envelope. Double wood studs of 38x89 mm (2"x4") with blown-in cellulose insulation and well-sealed vapor barrier were installed. The thermal resistance of the insulation for exterior walls including basement walls and roof were 10.57 $m^2 \cdot {}^\circ C/W$ and 14 $m^2 \cdot {}^\circ C/W$ respectively. Triple-glazed windows with two low-E coatings; argon gas filled were used having a total thermal resistance of 0.88 $m^2 \cdot {}^\circ C/W$. A solar hot-water system with 16 m^2 solar panels, used to heat water in a large tank was installed on the roof of this house. Hot water was used to heat the domestic water and to heat the house via water-to-air heat exchanger system. The measured infiltration rate of this house after the renovations was 0.47 ach at 50 Pa. The monitoring results revealed that the annual energy consumption was 14279 kWh or 46.9 kWh/m^2. Table 2.1 presents the house energy performance during year 1999.

Table 2.1. Energy performance of Dumont's house in year 1999

Item	Energy consumption [kWh]	Percentage of total [%]
Space heating	7 047	49.3
Lights and appliances	4 657	32.6
Domestic hot water	1 980	13.9
Water-to-air heat exchanger	595	4.2
Total	14 279	100

The air infiltration rate through the building envelope has a significant impact on energy consumption and cost. In his survey of 180 existing houses in Montreal, Canada Zmeureanu (2000) stated two levels of renovations, which were applied to reduce the air leakage and the energy consumption of houses: (i) renovations at level 1 to reach to 3.3 ach at 50 Pa, and (ii) renovations at level 2, to reach to 1.5 ach at 50 Pa. Table 2.2 illustrates the initial cost and energy savings due to the different levels of infiltration rate.

Table 2.2. Energy savings due to airtightness increase of sample houses

Construction Year	Air change rate at 50 Pa pressure difference [ach]	Renovation at level 1		Renovation at level 2	
		Initial cost [$]	Energy savings [$/y]	Initial cost [$]	Energy savings [$/y]
< 1921	7.3	3 774	93	5 331	131
1921 - 1945	7.7	1 310	112	4 222	126
1946 – 1960	7.7	1 597	145	4 134	280
1961 – 1970	6.9	1 918	58	4 547	90
1971 – 1980	6.9	1 325	111	4 279	280
1981 – 1985	5.3	1 095	188	4 177	130
1986 – 1990	4.9	1 483	128	3 919	223
> 1990	5.3	---	---	4 956	113

In the project of two-family house in Massachusetts, USA (Prahl, D. 1998), several problems were indicated including the use of single-pane windows and the deterioration of sheathing of the exterior walls and the insulation of foundation walls. The renovations included adding new thermal insulation for the basement walls, installing 0.2 m double stud wall system with sprayed cellulose insulation and continuous polyethylene vapor barrier, and using double-glazed windows with low-E coatings and filled with argon. The operating cost for heating energy after renovations was between US$ 320 to $ 400 for 270 m^2 of heated floor area. The incremental cost was estimated at US$ 11400.

Table 2.3. Estimated annual savings pre-retrofit vs. post-retrofit conditions (US dollars)

Parameter	Year 1996	Year 1995	Year 1994
Annual operating energy cost (pre-retrofit)	1690	1690	1690
Annual operating energy cost (post-retrofit)	431	426	517
Approximate annual savings	1259	1264	1173

A considerable part of heat loss is due to the exterior windows. Improving the thermal properties of windows has been the main concern of many engineers to enhance the thermal properties of houses. Wills (2000) examined the impact of different window types (e.g. windows with double-glazing units) on the corresponding annual energy cost, compared with that of a prototype window with single-glazing units. The experimental conditions such as the size, location and the climate were similar for all window types. Table 2.4 (Wills, C. 2000) presents the impact of the different characteristics of windows on the corresponding energy cost.

Table 2.4. Impact of windows characteristics on the annual energy cost

Window type	Shading coefficient (SHGC)	Overall U-value [$W/m^2 \cdot {}^\circ C$]	Reduction of the annual energy cost [%]
Single glazing clear glass	0.76	7.14	0
Double glazing clear glass	0.56	2.78	29
Double glazing low-E coating with argon gas	0.52	2.0	36
Triple glazing, low-E coating with argon gas	0.25	1.37	43

In most of the case studies, the main means used by engineers to improve the thermal performance of buildings included increasing the thermal resistance of buildings envelope, upgrading the thermal properties of windows and increasing the airtightness of buildings. A second approach used by researchers to reduce the total energy consumption of buildings is reducing the initial or embodied energy of construction materials.

2.2.2 Embodied energy

The embodied energy of a product is defined as the sum of total energy required for this product throughout its various stages of manufacture, from raw materials to the finished product. It can be defined also as " the total primary energy that has to be sequestered from a stock within the earth to produce specific goods or services and return whatever waste produced, safely to earth" (Amato *et al.* 1996). The common definition (Mumma 1995) used by scientists is: "the embodied energy is an assessment that includes the energy required to extract raw materials from nature, plus the energy used in primary and secondary manufacturing activities to provide a finished product".

Embodied energy analysis methods

There are four analysis methods (Alcorn *et al.* 1996) for the embodied energy evaluation:

1- Statistical analysis

Statistical analysis uses the published statistics and data to determine the consumed energy by particular industries. This method is significant and quick, if the statistics and required information are sufficient, consistent and pertinent.

2- Input-output analysis

In this method, researchers employed the economic input-output tables of the nation's economy. They calculated the money flows to and from the energy producing sectors, traced the energy flows within the economy and equated the output money of each sector with its energy usage. The advantage of this method is that money transactions and energy transactions within the economy are calculated. The disadvantages are the aggregation of dissimilar products in different sectors and the equivalence assumed between the physical units and the monetary value.

3- Process analysis

The direct and indirect energy inputs to each process of the material production is calculated. This method produces accurate and specific results for the material embodied energy. The disadvantage is the long time and effort required for the implementation.

4- Hybrid analysis

Researchers incorporated the three methods mentioned above, especially the input-output and process analysis methods. They use the available data of process analysis method and substituted any missing information or conflicting data by using results from the input-output analysis method.

Recycled and reused materials

At the final stage of life cycle of the building, some materials can be reused such as stock bricks, windows and roofing. Recycling materials has advantages, that it has less impact on the environment. Such materials have much less embodied energy than the original product. Table 2.5 presents the comparison of embodied energy of some of building materials in primary and recycled forms (Amato *et al.* 1996).

Table 2.5. Comparison of embodied energy for primary and recycled materials

Material	Primary [GJ/ton]	Recycled [GJ/ton]
Aluminum	150-240	11-40
Steel	25-40	9-12
Glass	12-30	10
Copper	71-85	40-50

Results indicate a considerable reduction of embodied energy for the recycled materials with respect to the embodied energy for the materials in primary form. This reveals the significant impact for the proper selection of materials on the energy-efficient design.

Embodied energy impact on building design

The embodied energy has a remarkable contribution to the national energy consumption. For instance, the embodied energy is about 7% of national energy consumption in USA and New Zealand (Baird, G. 1994). Furthermore, the combustion of oil and gas, which are the main sources of energy used for materials manufacturing and the operating of the buildings, have a significant contribution to the CO_2 emissions to the environment. The CO_2 emissions are considered as one of the main causes of climate changes in the world.

Some researchers have compared the embodied energy of houses versus the operating energy. In order to express the significance of embodied energy, the calculated number of years of heating consumption is used. Table 2.6 illustrates the embodied and operating energy of some houses in Canada (Mumma, T. 1995).

Table 2.6. Embodied energy versus heating energy

Home type and location	Heating energy [GJ/year]	Embodied energy [GJ]	Embodied energy in years of heating energy
Conventional, Vancouver	101	948	9.4
Energy-efficient, Vancouver	57	1019	17.9
Conventional, Toronto	136	948	7.0
Energy-efficient, Toronto	78	1019	13.1

Results show that the more energy efficient the house is in terms of operating energy use, the larger contribution the embodied energy has on life-cycle energy use.

In Australia, Pullen (1994) estimated the average annual operating energy for 25 houses of average floor area of 165 m^2 to be 0.80 GJ/m^2. The estimated embodied energy was 10.3 GJ/m^2 including 5.9 GJ/m^2 for buildings materials, 4 GJ/m^2 for maintenance and refurbishment during the buildings life cycle, and 0.40 GJ/m^2 for construction. The embodied energy corresponds to about 18 years of annual energy consumption. This indicates the considerable impact of embodied energy on the total energy consumption.

In his study of semi-detached, two-story house in Montreal, Canada, Friedman *et al.* (1995) used this prototype house to investigate the impact of selecting different building materials on the energy savings of the house.

Table 2.7 (Friedman *et al.* 1995) presents the energy savings due to using materials with less embodied energy.

Table 2.7.Embodied energy savings by using alternative building materials

Building material	Environmental benefits	Embodied energy savings [MJ]
Sheathing Replacing plywood with oriented strand board	59% less embodied energy and efficient use of resources	17 493
Insulation Replacing fiberglass with cellulose	56% less embodied energy and less resource depletion	3 104
Roof shingles Replacing asphalt with cedar	43% less embodied energy and less resource depletion	2 952
Siding Replacing vinyl with cedar	92% less embodied energy and less resource depletion	38 124
Brick Replacing clay with concrete	55% less embodied energy	9 986
Flooring Replacing carpeting with parquetry & vinyl with ceramic	75% less embodied energy and less resource depletion 85% less embodied energy	8 347 3 995
Total		84 000

Results show that there are considerable environmental benefits from replacing the high-embodied energy materials with less embodied energy materials. It was calculated that the total savings were about 84000 MJ, which was equivalent to four years of energy required to heat this house.

From the previous discussion, the engineering approach is used by building engineers to upgrade the thermal performance of buildings through improving the thermal performance of building envelope and reducing the embodied energy of construction materials. The architectural approach is another approach used by architects to improve the energy-efficient design of buildings based on the rules of thumb.

2.3 Architectural approach

Generally, there are two approaches for buildings design:

1- Climatically rejecting design. In this method, combinations of building materials are designed to reject all influences of the external climate, both positive and negative. Insulated walls, pitched airy roofs, double-glazed windows, well-sealed air and vapor barriers are used in this system.

2- Climatically interactive design. In this method the external climate is considered and integrated within the building design. Architects developed this approach by incorporating the positive natural forces to improve the thermal performance of buildings.

Architects developed the building performance through improving: (i) the patterns of energy-efficient design, and (ii) the passive solar design. Most of research work in this field was performed in the 1970's and a lot of current research is based on the work done in this era.

2.3.1 Design patterns

The design patterns, used to improve the buildings performance were based on rules of thumb and the experience of architects and building designers from similar projects. The recommendations for the energy-efficient design are presented as follows:

- Building location

In Canada, low winter sunrays hit the facades facing the southeast to southwest. In Montreal, approximately 90% of sun output occurs between 9:00 AM and 3:00 PM in winter (Hutcheon *et al.* 1995). Therefore, it is essential to determine the site areas and building location, which receive the maximum sunrays during this period. Many researchers such as Stein *et al* (1992) recommended to place the open areas and gardens to the south and to remove obstructions from the south direction to increase the solar heat gains within buildings.

- Building shape and orientation

Building shape should be designed regarding to its location and sunrays impact. The optimum shape is the rectangular shape that is elongated to east-west axis to gain maximum solar heat from south facade in winter and reduce heat gains from the west and east facades in summer. Stein *et al* (1992) recommended the ratio of 3:1 between the southern facade to the eastern or western facades for the optimum building shape.

- Interior spaces design

Interior space design includes spaces areas, function and locations. Clarck (1978) recommended the bedrooms to be placed on the southeast and southwest facades, and the living areas to face the sunny places of the site at the southern facade. The garage, closets, and the staircases were suggested to be located close to the northern axis, as these facilities act as a buffer zone between the cold and warm areas.

- Windows

Locating the major glazing areas to the southeast and southwest to gain the maximum solar radiation in winter and reducing the glazing areas on the north, east and west facades is preferred. South-facing windows with double-glazed units and having the percentage of 20- 40% of space floor area were recommended (Mazria, E. 1979).

2.3.2 Passive solar design

Designers defined the passive solar system, as it is the system that collects and transports the heat gain from sun radiation within buildings via non-mechanical system. Three patterns for the passive solar design were identified (Howard *et al.* 1992): (i) the direct solar gain system, (ii) indirect solar gain system, and (iii) the attached greenhouse.

Direct solar gain system

The preliminary and simplest system for passive solar heating approach is the direct solar gain system. Sunrays directly penetrate and heat the required spaces within the building. Two elements are used for this system: windows as solar collector and internal mass (walls, floors) as thermal storage mass. The direct gain system is characterized by large amount of south facing glazing to gain the most available heat in winter. Movable insulation is suggested as well to prevent the heat loss during the cold night in winter.

Table 2.8 (Stein, *et al.* 1992) presents the rules of thumb for the area of doubled-glazed, south-facing windows as ratio of the required heated floor area.

Table 2.8. Rules of thumb for the glazing-to-floor area ratio in Canada

City	Glazing-to-floor area ratio	
	Low	High
Vancouver, British Columbia	0.13	0.26
Edmonton, Alberta	0.25	0.50
Winnipeg, Manitoba	0.25	0.50
Toronto, Ontario	0.18	0.36
Ottawa, Ontario	0.25	0.50
Normandin, Quebec	0.25	0.50
Dartmouth, Nova Scotia	0.14	0.28

The major problem confronting the designer of direct gain system is to prevent the daytime overheating and the temperature fluctuation; therefore, the thermal masses (Table 2.9) such as masonry or water walls are used.

Indirect solar gain system

In the indirect solar gain system, the sunrays first strike a thermal mass, which is located between the sun and the space. The sunrays. absorbed by the mass is converted to thermal energy (heat) and then transferred into the living space. Basically, there are two types of the indirect gain system: (i) the mass-wall system, and (ii) the roof ponds. The difference between the two systems is the location of the mass; one is contained in a wall and the other on the roof.

- Mass-wall system

This system consists of large south-facing glazing area and thermal mass such as masonry or water walls. The similar rules of thumb used for the glazing-to-floor area ratio (Table 2.8) are used for the indirect gain system. Table 2.9 (Mazria, E. 1979) presents the rules of thumb for the thermal mass for cold climate countries. A minimum thickness of 0.1 m for the mass wall is recommended.

Table 2.9. Rules of thumb of the thermal mass walls

Average outdoor temperature [°C]	Masonry wall area required for each $1 m^2$ of floor area $[m^2]$	Water wall area required for each $1 m^2$ of floor area $[m^2]$
- 10.0	0.72 – 1	0.55 – 1
- 7.0	0.6 – 1	0.45 – 0.85
- 4.0	0.51 – 0.93	0.38 – 0.7
-1.0	0.43 – 0.78	0.31 – 0.55

- Roof pond system

Roof ponds are used as a solar collector, heat storage and a radiator. Two types of roof ponds are used: (i) flat roof pond with sliding movable or folding panels, and (ii) slopped roof pond. The rules of thumb for the roof ponds design (Stein, *et al.* 1992) are as follows: (i) the thickness of roof pond is between 0.15 m to 0.3 m, (ii) the sloping angle is equal to the city latitude plus 15°, and (iii) the ratio between the solar collector area to the required heated space area is presented in table 2.10.

Table 2.10. Rules of thumb for the solar collector area of roof ponds

Item	British Columbia	Alberta	Manitoba	Ontario	Quebec
Ratio between the solar collector and space floor area	0.13	0.25	0.25	0.18	0.25

Greenhouse system

The attached greenhouse is a combination of direct and indirect solar gain systems. The greenhouse (sunroom) is constructed onto the south side of the building with a mass wall, separating the greenhouse from the building. Since, it is directly heated by sunlight, the greenhouse functions as a direct gain system. However, the space adjacent to the greenhouse receives its heat from the mass wall.

The general guidelines cited by Mazria (1979) for greenhouse system of cold climate countries such as Canada are: (i) elongating the greenhouse in the east-west direction to increase its glazing area facing the south, (iii) using mass walls such as masonry with a minimum thickness of 0.2 m, and (ii) the ratio between the south-facing, double-glazing area and the adjacent living space is 1.5.

Most of design patterns for passive design systems and solar heat gains, used by architects were based on experience and rules of thumb. However, the literature search revealed that there were not adequate studies to examine the prescribed design patterns on a scientific basis to ensure the accuracy of the information derived from the rules of thumb. The following section discusses the advanced programs, established in Canada for energy-efficient houses.

2.4 Advanced approaches

Large-scale studies were established by public and private institutions to improve the energy performance of houses. Over the last two decades, the Canadian government sponsored major programs in the field of energy-efficient design of residential buildings including: (i) the R-2000 program, and (ii) the Advanced Houses program.

2.4.1 R-2000 program

The R-2000 Home Program provides the basis for the design and the construction of new residential buildings and addresses the relevant environmental aspects of buildings.

This program was sponsored by the following Canadian institutions: Energy, Mines and Resources Canada; Canadian Home Builders Association (CHBA); Canada Mortgage and Housing Corporation (CMHC); and Heating, Refrigeration and Air Conditioning Institute in Canada. The main objectives of the program are as follows:

- Reduction of the energy consumption by 50% compared with a conventional house;
- Use of materials that have less impact on the environment; and
- Improvement of the indoor air quality.

The insulation level is one of effective tools used in R-2000 to improve the energy performance of houses. The minimum levels of insulation (Natural Resources Canada, 1999) are presented in table 2.11.

Table 2.11. Minimum requirements of the insulation levels in R-2000 houses

Degree day zone [°C]	Thermal resistance [$m^2 \cdot {}^oC/W$]		
	Exterior walls above grade	Exterior walls below grade	Insulated ceiling and attics
Up to 3500	2.80	1.80	4.70
3501 - 6000	3.60	1.80	5.60
6001 - 8000	4.20	2.80	6.40
8001 and over	4.70	3.60	7.10

It is recommended that windows be double-glazed with a minimum air space thickness of 12.5 mm between panes. Metal window frames should be thermally broken. Continuous caulking and weather-stripping between window's frame and wall are recommended, as shown in figure 2.2 (Office of energy efficiency, 2000).

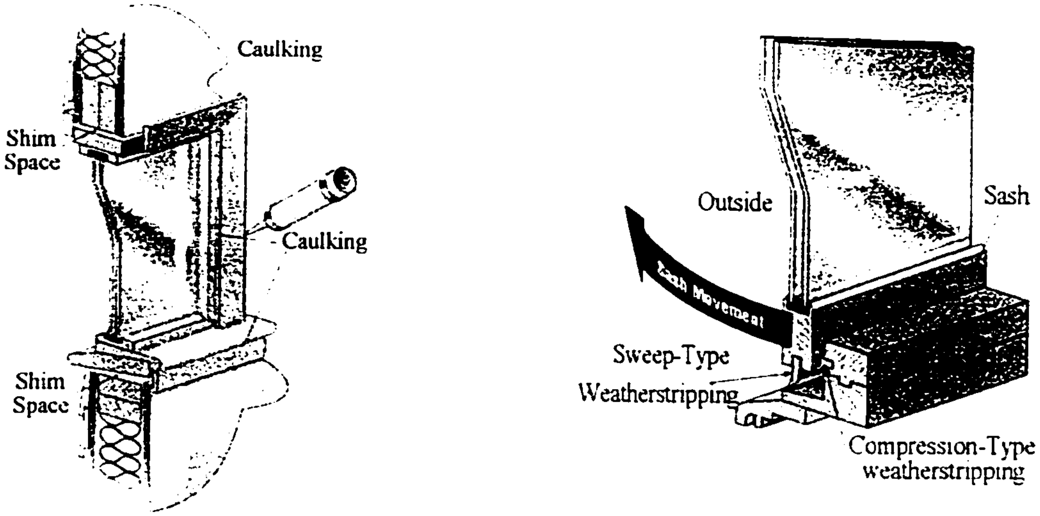


Figure 2.2. Exterior windows design at R-2000 program

The Normalized Leakage Area (NLA) of building envelope is required to be less than $0.7 cm^2/m^2$ of the envelope area and the air change rate at 50 Pa to be less than 1.50 ach. Infiltration tests can be implemented by using Fan Depressurization Method or by any equivalent methods approved by the Canadian Home Builders Association. The target of annual energy consumption of an R-2000 house (Natural Resources Canada, 1999) is established as follows:

$$\text{Annual total energy target} = Q_s + Q_w \tag{2.1}$$

where:

Q_s = space heating energy consumption target [kWh]; and

Q_w = domestic hot water energy consumption target [kWh].

$$Q_s = S\,(60\,DD/6000)\,(35 + V/2.5) \tag{2.2}$$

where:

S = 1.25 for fuel-fired space heating system, or 1.0 for electric heating system [kWh];

DD = heating degree days for the location [^{o}C]; and

V = Interior heated volume, including basement [m^3].

$$Q_w = 4745 * W * (55 - T_w) / (55 - 9.5) \tag{2.3}$$

where:

T_w = cold water supply [^{o}C]; and

W = 1.72 for fuel-fired systems, or 1.075 for electric systems [kWh].

2.4.2 Advanced Houses program

Advanced Houses program was established by the Canadian Home Builders Association; Canada Mortgage and Housing Corporation (CMHC); and Canada Center for Mineral and Energy Technology (CANMET). Advanced Houses program addressed many aspects such as thermal performance of houses, cost reduction, technology transfer, consumption of the natural resources, waste products and energy efficiency.

Building enclosure

Some of the techniques and systems used in the Advanced Houses projects to improve the building enclosure thermal performance (Hickling Corporation, 1993) are presented.

The foundation system design used in the Advanced Houses ranged from insulated slab-on-grade to full insulated concrete basement with external or internal insulation. Advanced Houses applied some of the advanced techniques to decrease the heat loss to ground such as: (i) pre-cast foundation with special cavities filled with cellulose insulation in addition to the internal insulation within the wood stud wall attached to the inner concrete wall of basement. (ii) integrated heating slab installed in insulated foundation floors to provide sufficient heating. and (iii) rigid insulation between footing foundations and basement walls to prevent thermal bridges.

Framing systems differed from a project to another. depending on the location. climate and construction techniques. Most of Canadian Advanced Houses used double wall 38x89 mm (2"x4") framing with glass fiber insulation. The exterior walls of houses have average U-value of 0.23 $W/m^2 \cdot {}^oC$ with a standard deviation of 0.13 $W/m^2 \cdot {}^oC$.

Thermal bridges. infiltration. connection between walls and roof and continuity of vapor and air barriers were the main features for improving the roof system. New concepts were established in this area e.g. double roof system with light construction for interior roof. The integrated roof system with solar system or photovoltaic panels was applied in some Advanced Houses as well to improve the energy performance of houses.

Most of the Advanced Houses in Canada used triple glazed with low emissivity coating and argon gases, while windows frames were made of extruded glass fiber. The U-value of windows was between 0.50 to 1.5 $W/m^2 \cdot {}^oC$.

Reflective blinds and automated revolving reflectors were used as well to reduce the excessive solar radiation.

The average air leakage of the eleven case studies of the Advanced Houses in Canada (Hickling Corporation, 1993) was between 0.50 to 1.50 ach at 50 Pa pressure difference. Often, the polyethylene was implemented as air and vapor barriers; weather-stripping and caulking were used to assure the continuity of air barrier and to increase the buildings airtightness. Mechanical ventilation with heat recovery system was extensively used for the airtight houses.

Case Studies

The NOVTEC house (Energy mines and resources *et al.* 1993) is an example of the Advanced Houses. The house was designed and built in Laval, Quebec in the 1990's. The house consisted of two floors and mezzanine with a total built up area of 210 m^2. Exterior walls were built with 38 x 89 mm studs and total thickness of 200 mm. By using two layers of rigid insulation fixed on the wood studs, the total thermal resistance of exterior walls was 5.46 $m^2 \cdot {}^{\circ}C/W$. A combination of three roof assemblies: cathedral roof, trussed roof and roof terrace were applied in this project. The thermal resistances of the truss roof and the cathedral roof were 10.02 and 7.75 $m^2 \cdot {}^{\circ}C/W$ respectively. The Integrated home comfort system contained two ground source heat pumps, and 550 m spiral coil embedded in the ground to extract heat from the ground in the winter and reject heat in the summer. The total annual electrical energy consumption of the NOVTEC house was 11864 kWh or 57 kWh/m^2.

Table 2.12 presents a brief summery of some of the Advanced Houses built in Canada. (Hickling Corporation, 1993).

Table 2.12. Examples of Advanced Housed constructed in Canada

Parameters	Canadian advanced house	Innova house	Waterloo green home	CMHC healthy houses	Falir homes
Location	Ontario	Ontario	Ontario	Ontario	Manitoba
Heating degrees days [18 °C]	4321	4673	4164	3644	5871
Cooling degrees days [18 °C]	255	230	237	346	178
Heated floor area [m^2]	418	274	234	112.9	170
Heated volume [m^3]	N/A	682	625	N/A	408
U-value of Roof [$W/m^2 \cdot °C$]	0.094	0.095	0.094	0.14	0.1-0.2
U-value of Floor [$W/m^2 \cdot °C$]	0.83	0.35	0.71	N/A	0.0-0.8
U-value of external wall [$W/m^2 \cdot °C$]	0.142	0.15	0.17	0.19	0.14-0.30
U-value of windows [$W/m^2 \cdot °C$]	1.06	1.06-1.2	1.04	0.87	N/A
Airtightness [ach] @ 50 Pa	0.9-1.35	1.5	1.5	N/A	0.40-1.8
Space heating [kWh/m^2]	25	27.4	22.4	N/A	N/A
Total energy usage [kWh/m^2]	49	69.0	49.7	N/A	N/A

The literature search revealed that the techniques utilized by the Advanced Houses in cold climates were based on using hyper thermal insulation for building enclosure; triple glazing layers for windows, high-efficient mechanical and heat recovery systems.

2.5 Summary and conclusions

Several researches and case studies in the area of energy efficiency have been presented in this chapter including: (i) the engineering approach, (ii) architectural approach, and (iii) the advanced Canadian programs for houses including the R-2000 and Advanced Houses programs. The results are briefly summarized in the flowing points:

- The engineering approach is based on theoretical developments, experiments and monitoring of buildings. This approach is used extensively by building engineers to improve the energy performance of buildings and to overcome thermal performance problems arising after years of building operation. Increasing the thermal resistance and the airtightness of building envelope and improving the thermal properties of windows in addition to reducing the embodied energy of construction materials were the major means used by engineers to improve the thermal performance of buildings.

- The architectural approach is developed by architects to improve the energy-efficient design of buildings. The passive design and the use of solar heat gains were the main means used in this approach. Although such means have a considerable impact on building performance, they were based on the rules of thumb such as elongating the building in the east-west direction and increasing the south facing glazing areas to increase the solar gains within buildings.

- Two advanced programs were established in Canada in last decades to improve the energy performance of houses including: R-2000 program and Advanced Houses program. Both programs were developed to improve the thermal performance of conventional houses. Most of the techniques and concepts used in these programs were based on engineering approach including the increase of thermal resistance and airtightness of buildings envelope in addition to the improving of mechanical and ventilation systems.

From the previous discussion, a portrait of current means to improve the energy performance of houses was presented. However, the designer facing this array of design solutions is often left on his own. There is a need for a tool to support the complex decision making of energy-efficient design. In addition, more consideration for the integration between the engineering approach and architectural approach is required. This integration could yield further means to be used during the design to improve the energy performance of buildings.

In this research, the analysis of a sustainable house, which uses many of the energy-efficient techniques, discussed so far is performed. Several design alternatives for the base case house, based on both parametric and non-parametric approaches have been developed and their performance has been evaluated using the life-cycle analysis. The analysis of the design alternatives is used to improve the energy-efficient design of houses and to develop a decision support system, used to support the decision-making of building designers.

CHAPTER 3

DESCRIPTION OF BASE CASE HOUSE AND BLAST SIMULATION PROGRAM

The objective of this chapter is to analyze the Ray-Vision house. which is used as a base case house in this study. including the house design and construction materials from the point of view of energy efficiency. An introduction to BLAST simulation program. which is used to analyze the energy performance of the base case house. is also presented

3.1 Introduction to the Ray-Vision house

Ray-Vision house is a duplex-apartment house built in Longueuil. on the south shore of Montreal. Canada in the year 2000. The house was designed and built with the goal of being energy-efficient. The description of the house comprises all aspects of architectural design, material characteristics and energy-efficient concepts used for the house.

This information was derived from the architectural drawings and specifications and from several visits to the house site during the construction. The input file of BLAST program was built based on the previous information and utilized to establish the computer model of the house. The Ray-Vision house, addressed in this chapter, is used as a base case for comparing the design alternatives proposed in the following chapters.

3.1.1 Architectural design

The architectural design of the house includes the description of the site layout, floor plan, facades design and house detailed sections comprising the material characteristics of house envelope.

Layout and house floor plans

The Ray-Vision house was built on north-south direction with an open space at the south, a main street at the north and two neighbors from the east and west directions. Both neighborhood buildings are at a distance of almost 6 m from the house. Although the neighborhood buildings have no impact on the shading or sunrays obstruction of the northern and southern facades of the house, they have a considerable impact on the eastern and western facades. Figure 3.1 illustrates the layout of the house.

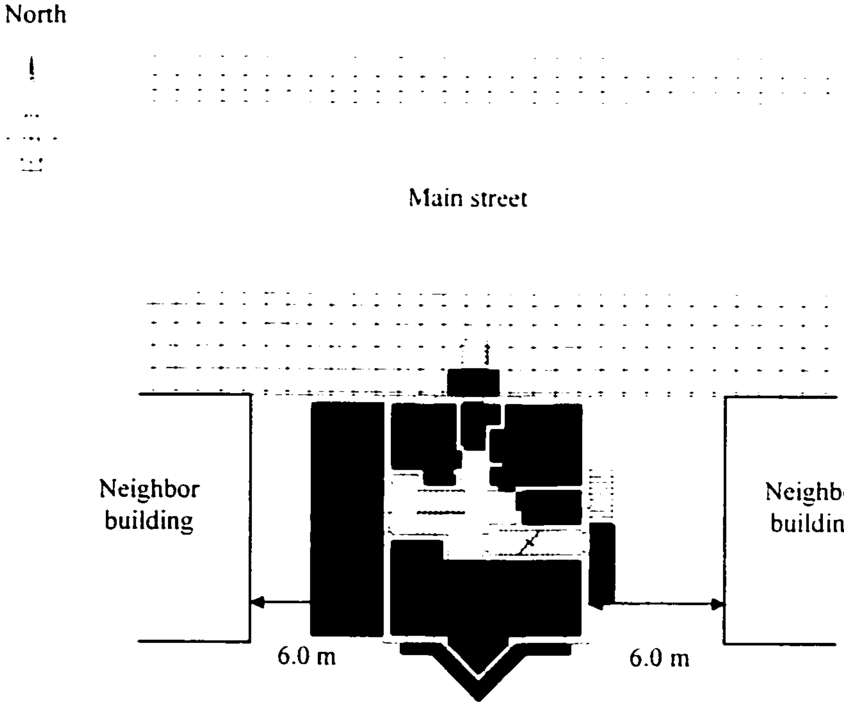


Figure 3.1. Layout of the base case house

The house consists of two apartments: a duplex apartment including the basement and ground floor for the owner family and the tenant apartment on the second floor. The total built-up area for the basement is 105.78 m^2; ground floor is 103.28 m^2 while it is 100.46 m^2 for the second floor. The house was designed with large glazing facing south to benefit from sunshine in the winter. The day-used spaces such as living room, dining room and kitchen were arranged to the south side to benefit from the period of sunshine during the day, while the night-used spaces such as bedrooms were located to the other side, mainly to the north facade.

The architectural design for the basement, ground and first floor plans of the house, interior partitions and the house operating conditions were used for determining the thermal zones. The thermal zone of a house is defined by BLAST (1991) as the air volume at a uniform temperature with a given (defined) occupancy or profile of thermal control. Therefore, the building spaces, which have similar temperature and operating control schemes, and have similar external thermal loads, were combined in one thermal zone. A number of 13 thermal zones were defined, plus the attic.

Figures from 3.2 to 3.4 present the architectural design of the base case house and the proposed thermal zones for each floor.

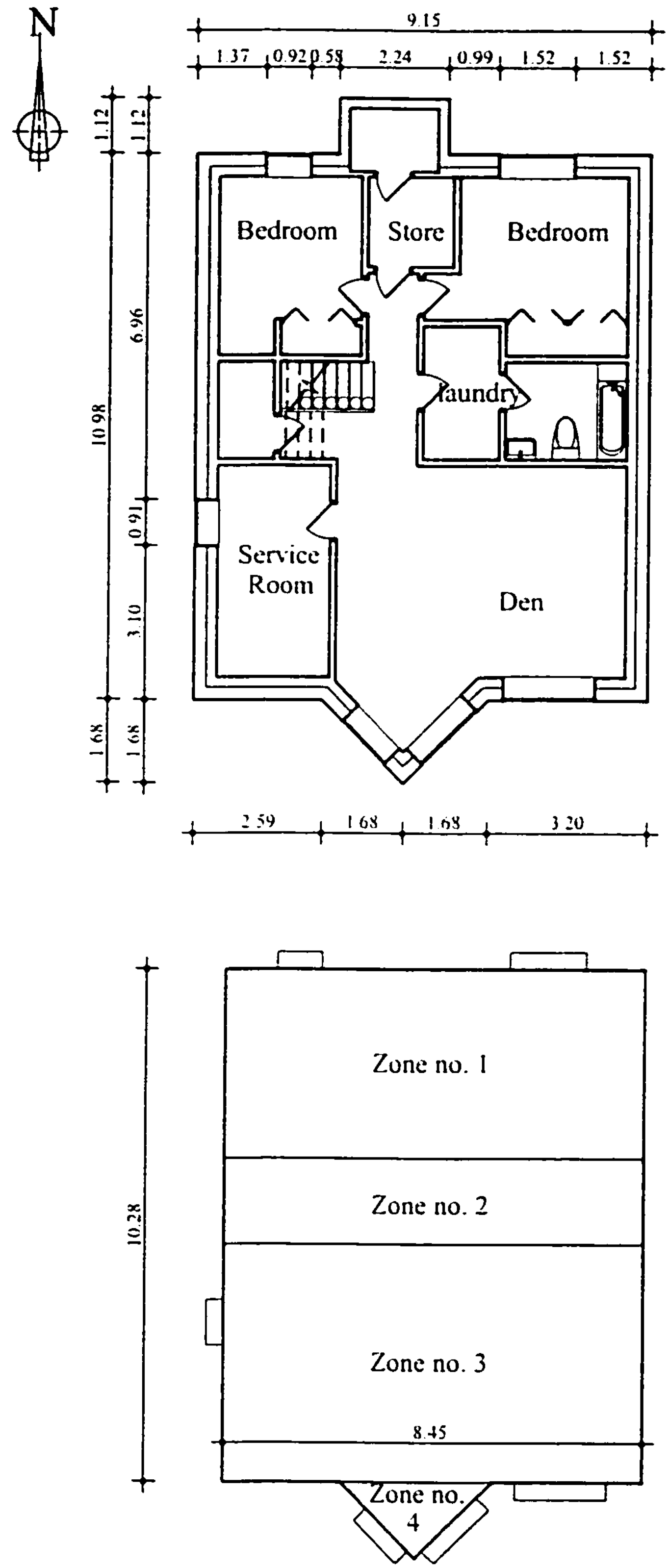


Figure 3.2. Basement plan and related thermal zones of the base case house
Scale 1:150

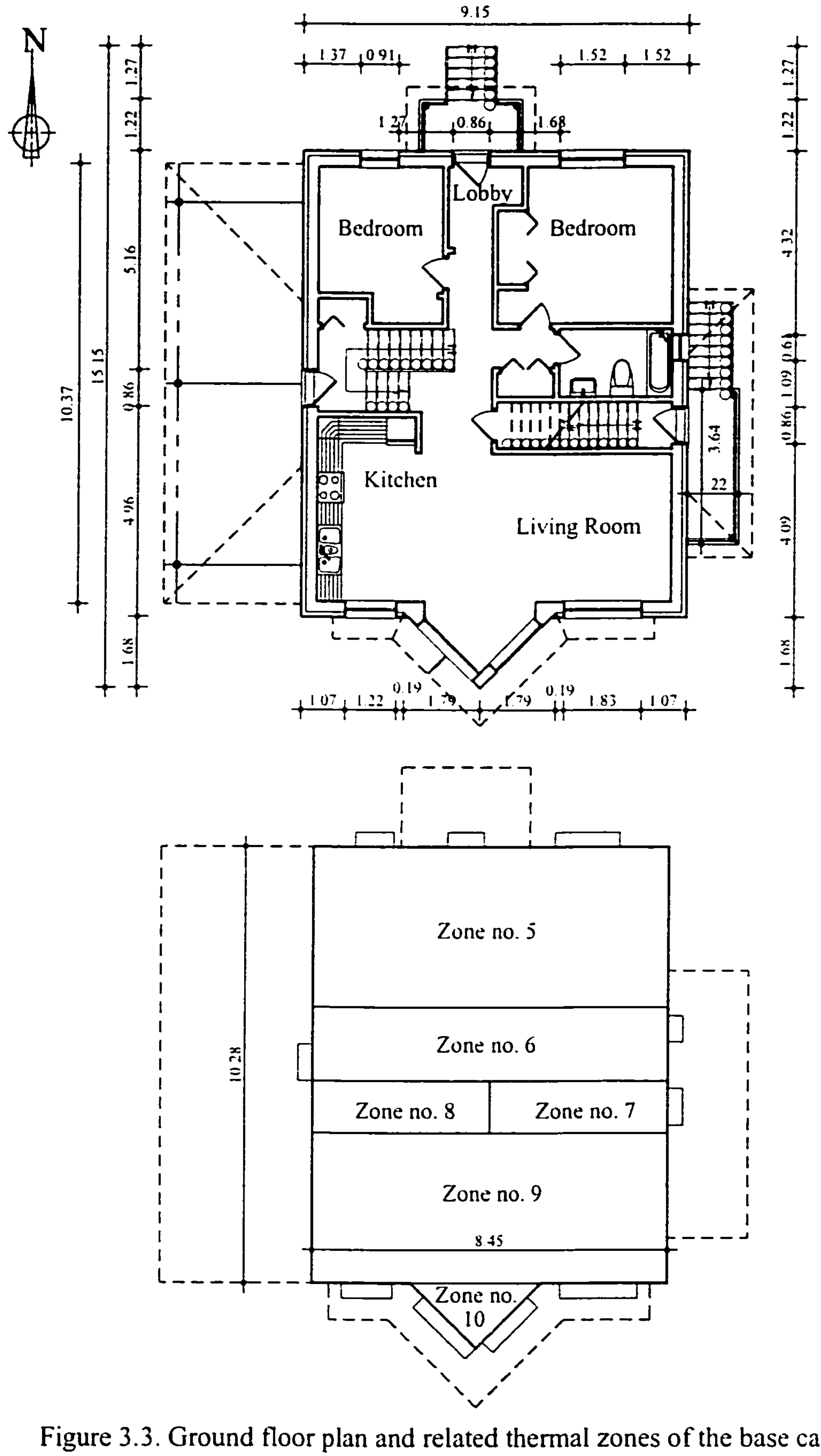


Figure 3.3. Ground floor plan and related thermal zones of the base case house
Scale 1:150

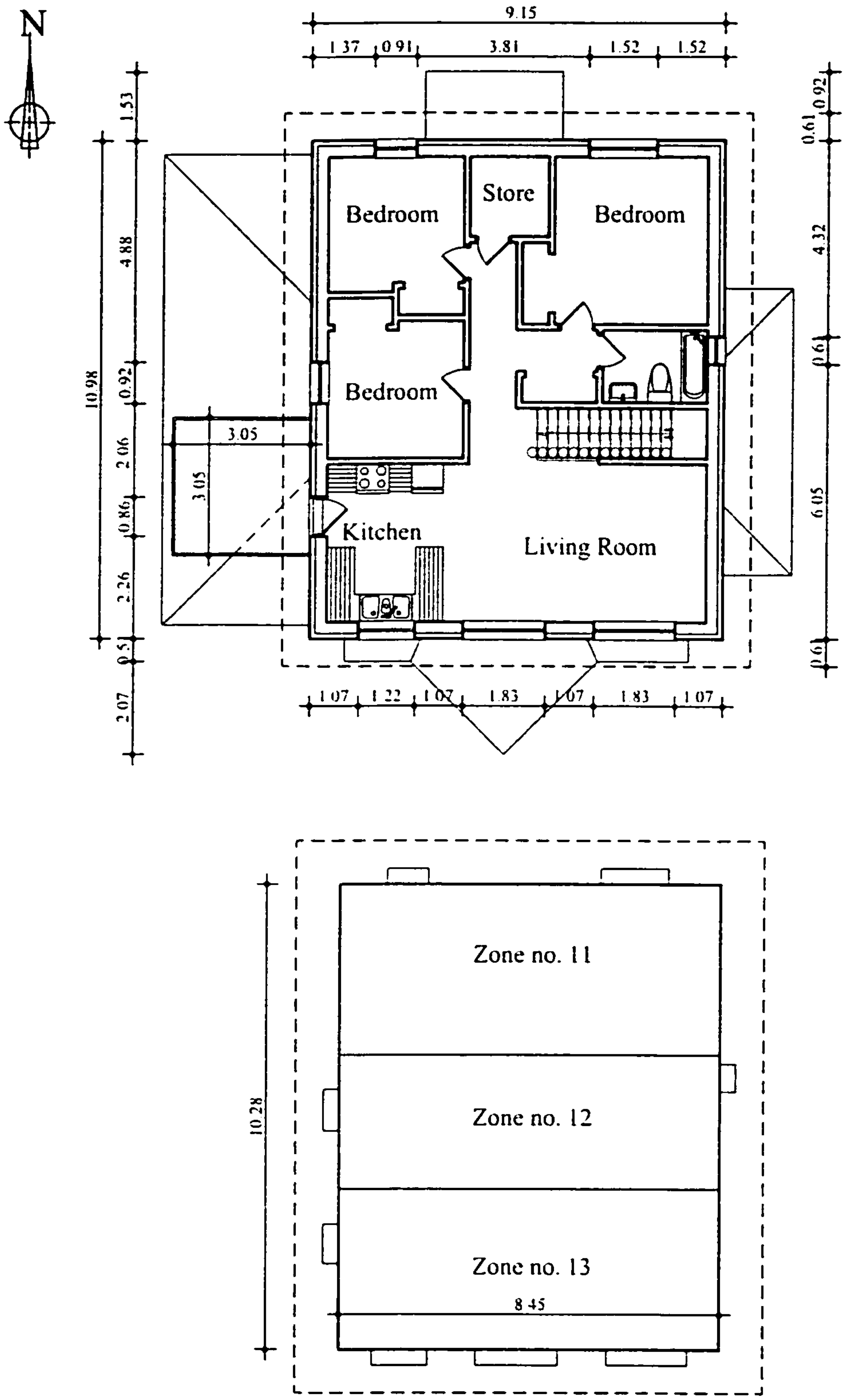
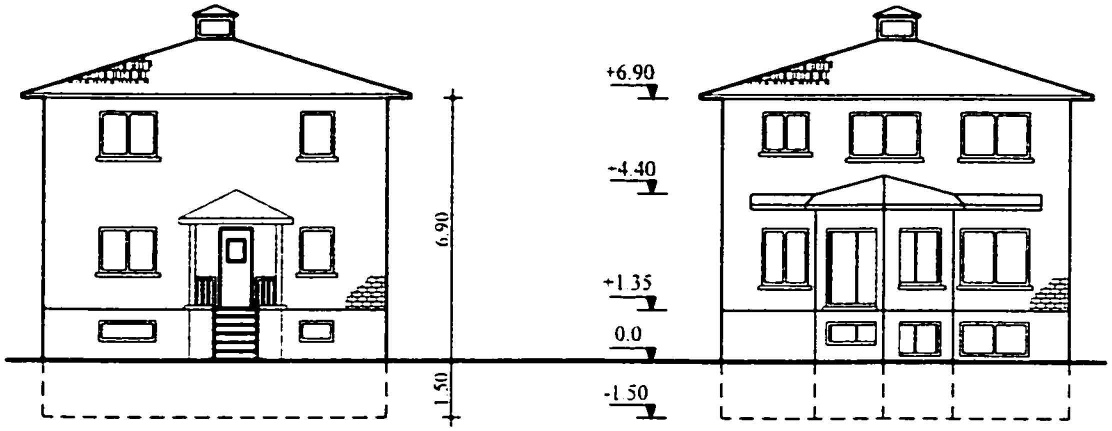


Figure 3.4. First floor plan and related thermal zones of the base case house
Scale 1:150

The basement (Figure 3.2) consists of two bedrooms located at the northern facade; a den directed to the south; a storage used as a cold room; laundry and a bathroom. The ground floor (Figure 3.3) consists of two bedrooms, living room, kitchen and a bathroom. The second floor (Figure 3.4) consists of three bedrooms located at the northern and eastern facades; the living room and the kitchen are located at the southern facade, while a large balcony opens from the kitchen, is located at the western facade. The main stair is placed inside the house connecting the basement and ground floor, while the secondary stair is located at the eastern facade and is used to connect the second floor to the outside.

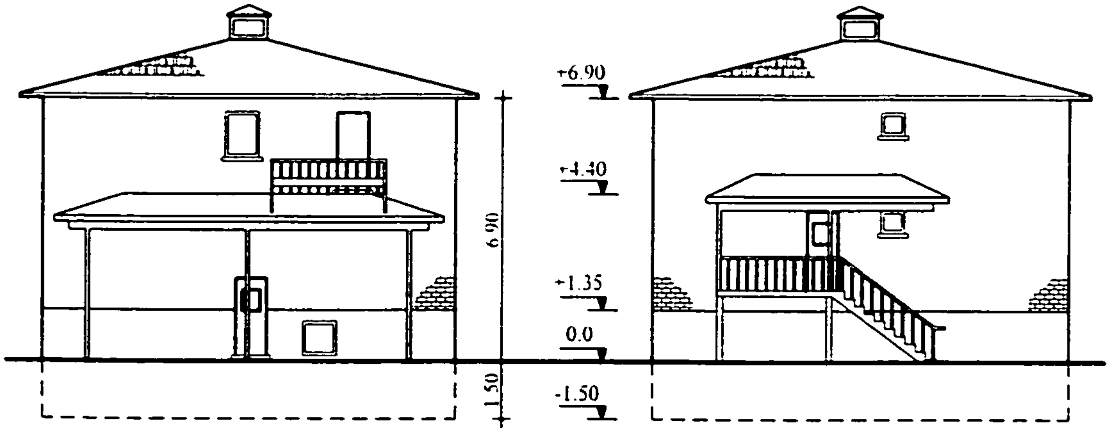
Design of house facades

Maximizing the glazing area of the south facade and minimizing it on the other facades was one of energy-efficient concepts used by the designer for the house facade design to reduce the heating loads by increasing the solar gains within the house. For instance, the glazing area accounts for 28.75% of south facade, 1% for east facade and 2% for west facade, which are close to neighbour buildings, and 11.38% of north facade. Double-glazed windows with a thermal resistance of 0.57 $m^2{\cdot}{}^{o}C/W$ were installed to reduce the heat loss through windows. Sun shadings were used to reduce the overheating during summer, including a garage shed of 3.5 m at the western facade. Figure 3.5 presents the design of the house northern, eastern, western and southern facades.



Northern Facade

Southern Facade



Western Facade

Eastern Facade

Figure 3.5. The base case house facades
Scale 1/200

Material characteristics of the building envelope

The house envelope includes the basement walls, above ground walls and the attic. The energy-efficient design of the envelope was based on increasing the house tightness and the thermal resistance to improve the thermal performance of the house.

Windows of glass fibre pultrusion frames, glazed with sealed double-glazed units with low-emissivity coating and filled with argon were installed, having a thermal resistance of 0.57 $m^2 \cdot {}^oC/W$, which exceeds the minimum value of 0.35 $m^2 \cdot {}^oC/W$ prescribed by the energy-related regulations of Quebec (1992). The above ground exterior walls were constructed using 38 mm x 140 mm wood studs with 140 mm thick blown-in cellulose. On the exterior side of the wood studs, horizontal 38 mm x 38 mm furring strips were installed and covered with an exterior sheathing. A sprayed in-situ polyurethane insulation filled the space between the sheathing and the wood studs to minimize the thermal bridges, increase the thermal resistance of the assembly and provide a continuous airtight assembly. In addition, a polyurethane insulation was installed around the elements puncturing the exterior walls to reduce the air infiltration and prevent thermal bridges through windows frames and the wall. A well-sealed 6 mm vapor barrier was used to prevent water vapour transmission and was the air barrier for the roof assembly.

Figures from 3.6 to 3.8 present the detailed sections of the house envelope and the calculation of thermal resistance values of the different components of the envelope.

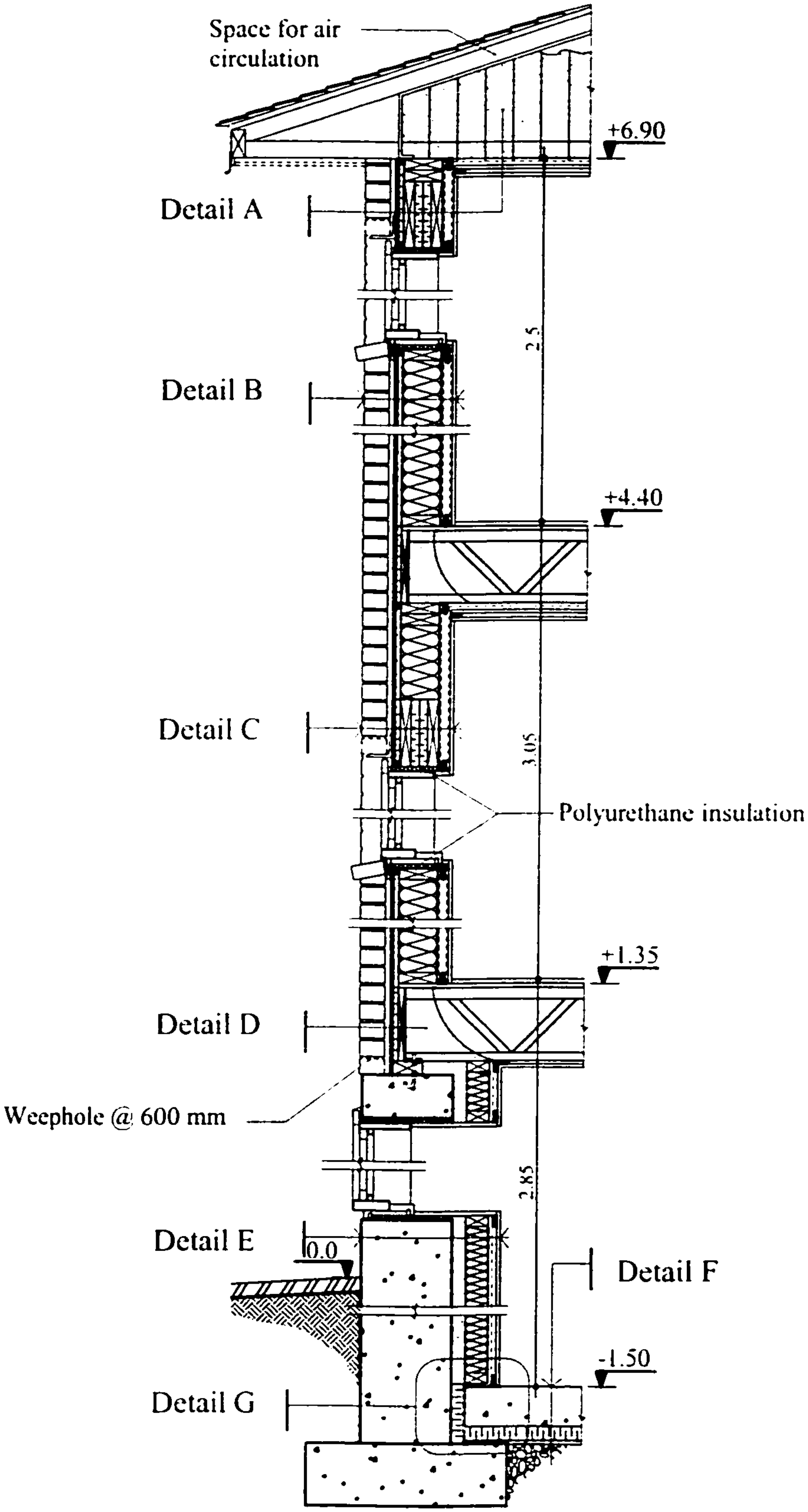
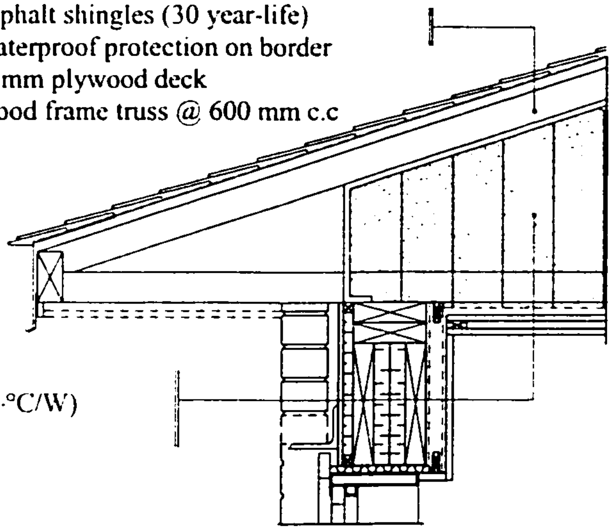
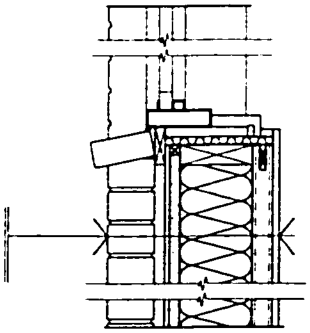


Figure 3.6. Section of the base case house envelope
Scale 1:25

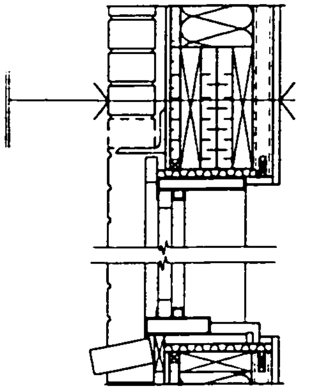


Asphalt shingles (30 year-life)
Waterproof protection on border
13 mm plywood deck
Wood frame truss @ 600 mm c.c

Detail A
400 mm cellulose insulation (10.56 m²·°C/W)
13 mm asphalt impregnated fibre board (0.23 m²·°C/W)
6 mm polyethylene vapor barrier (0.0 m²·°C/W)
13 mm gypsum board (0.08 m²·°C/W)
Total = 10.87 m²·°C/W



Detail B
90 mm brick veneer (0.08 m²·°C/W)
20 mm air space (0.21 m²·°C/W)
Wind barrier, SBPO housewrap (0.02 m²·°C/W)
13 mm asphalt impregnated fibre board (0.23 m²·°C/W)
Wood studs 38x38 @ 600 mm c.c; filled with 38 mm of polyurethane insulation (1.76 m²·°C/W)
Wood studs 38x140 @ 0.600 mm c.c; filled with 140 mm cellulose insulation (3.5 m²·°C/W)
6 mil. polyethylene vapor barrier (0.0 m²·°C/W)
13 mm gypsum board (0.08 m²·°C/W)
Total = 5.88 (m²·°C/W)

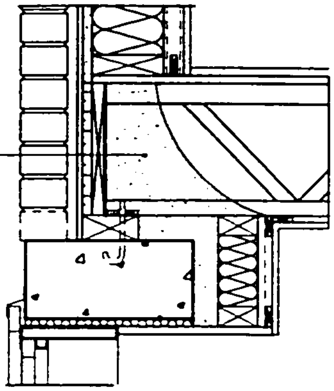


Detail C
90 mm brick veneer (0.08 m²·°C/W)
20 mm air space (0.21 m²·°C/W)
Wind barrier, SBPO housewrap (0.02 m²·°C/W)
13 mm asphalt impregnated fibre board (0.23 m²·°C/W)
38 mm extruded polystyrene insulation (1.32 m²·°C/W)
Wood joist 38x240 (0.40 m²·°C/W)
60 mm extruded polystyrene insulation (2.2 m²·°C/W)
Wood joist 38x240 (0.40 m²·°C/W)
6 mil. polyethylene vapor barrier (0.0 m²·°C/W)
13 mm gypsum board (0.08 m²·°C/W)
Total = 4.94 m²·°C/W

Figure 3.7. Materials characterstics of house envelope for details A, B and C
Scale 1:15

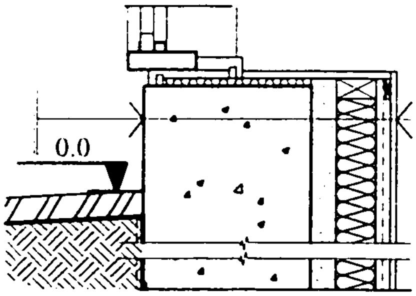
Detail D

90 mm brick veneer (0.08 m^2·°C/W)
20 mm air space (0.21 m^2·°C/W)
Wind barrier, SBPO housewrap (0.02 m^2·°C/W)
13 mm asphalt impregnated fibre board (0.23 m^2·°C/W)
38 mm extruded polystyrene insulation (1.32 m^2·°C/W)
Wood joist 38x240 (0.40 m^2·°C/W)
100 mm polyurethane insulation (4.22 m^2·°C/W)
Total = 6.48 m^2·°C/W



Detail E

250 mm reinforced concrete (0.32 m^2·°C/W)
50 mm polyurethane insulation (2.11 m^2·°C/W)
Wood studs 38x89 @ 600 mm c.c; filled with 89 mm cellulose insulation (2.3 m^2·°C/W)
6 mil. polyethylene vapor barrier (0.0 m^2·°C/W)
13 mm gypsum board (0.08 m^2·°C/W)
Total = 4.81 m^2·°C/W



Detail F

Compacted soil and aggregated gravel
6 mil. polyethylene vapor barrier (0.0 m^2·°C/W)
50 mm extruded polystylene insulation (1.76 m^2·°C/W)
80 mm slab-on-grade concrete (0.10 m^2·°C/W)
Total = 1.86 m^2·°C/W

Detail G

250 mm reinforced concrete (0.32 m^2·°C/W)
50 mm extruded polystyrene insulation (1.76 m^2·°C/W)
6 mm polyethylene vapor barrier (0.0 m^2·°C/W)
80 mm slab-on-grade concrete (0.10 m^2·°C/W)
Total = 2.18 m^2·°C/W

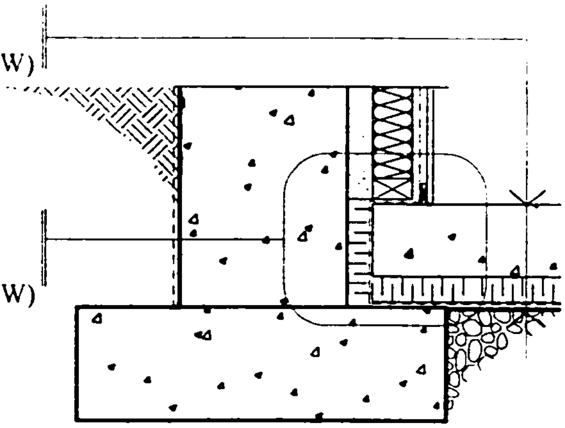


Figure 3.8. Materials characterstics of house envelope for details D, E, F and G
Scale 1:15

The overall thermal resistance for exterior walls was calculated accounting for windows location (Detail C, Figure 3.7) and the connection between the floors and exterior walls (Details D and G, Figure 3.8). Moreover, the wood studs creating the thermal bridge effect, were considered in the calculations as well. The area-weighted average method was performed to calculate the average thermal resistance of the above ground walls by utilizing the following formula:

$$Th_{average} = (Th_B * A_B + Th_C * A_C + Th_D * A_D + Th_{ST} * A_{ST}) / A \quad (3.1)$$

where:

$Th_{average}$ = average thermal resistance of the opaque wall [$m^2 \cdot {}^oC/W$];

A = gross wall area [m^2];

Th_B = thermal resistance of the exterior wall (Detail B, Figure 3.6) [$m^2 \cdot {}^oC/W$], with area A_B [m^2];

Th_C = thermal resistance of the exterior wall (Detail C, Figure 3.6) [$m^2 \cdot {}^oC/W$], with area A_C [m^2];

Th_D = thermal resistance for floor and wall connection (Detail D, Figure 3.7) [$m^2 \cdot {}^oC/W$], with area A_D [m^2];

Th_{ST} = thermal resistance of the exterior wall through wood studs [$m^2 \cdot {}^oC/W$], with area A_{ST} [m^2].

By applying formula 3.1, the average thermal resistance of the above ground walls is equal to: $5.88 * 0.65 + 6.48 * 0.1 + 4.94 * 0.05 + 3.6 * 0.2 = 5.43\ m^2 \cdot {}^oC/W$.

Similarly, the average thermal resistance of the basement walls is equal to:

$4.81 * 0.73 + 2.18 * 0.05 + 4.81 * 0.02 + 3.31 * 0.2 = 4.40\ m^2 \cdot {}^oC/W$.

The high thermal resistance for the envelope assembly was achieved by increasing the amount of thermal insulation. The airtightness was increased by using a continuous air barrier whereas the main element was the sprayed-in-situ polyurethane insulation, and also using well-sealed 6 mm vapour barrier, continuous weather-stripping and caulking for window frames. Hence, the calculated thermal resistance of the above ground exterior walls is equal to 5.43 $m^2 \cdot {}^oC/W$, which exceeds the minimum value of 3.4 $m^2 \cdot {}^oC/W$ prescribed by the regulations of Quebec (1992). The basement walls, and the roof have a thermal resistance of 4.4 and 10.87 $m^2 \cdot {}^oC/W$, respectively, compared with 2.2 and 5.3 $m^2 \cdot {}^oC/W$ prescribed by the same regulations. Table 3.1 presents the thermal characteristics of the house envelope and the corresponding thermal resistance of the regulations of Quebec (1992).

Table 3.1. Thermal resistance of base case house envelope vs. Quebec regulations

Building components	Thermal resistance of the house [$m^2 \cdot {}^oC/W$]	Minimum thermal resistance of Quebec regulations [$m^2 \cdot {}^oC/W$]
<u>Building envelope</u>		
Roof (attic)	10.87	5.3
Walls above ground level	5.43	3.4
Walls below ground level (basement walls)	4.4	2.2
Exterior windows	0.57	0.35

The blower door test, described in chapter 4, revealed that the air infiltration rate at 50 Pa is equal to 1.25 ach. The literature search shows that the minimum requirements for infiltration rate of the R-2000 houses must not exceed 1.5 ach at 50 Pa. This indicates that the base case house is a well-sealed and airtight house.

3.1.2 Energy-efficient design of the base case house

The Ray-Vision house was designed and built to be an energy-efficient house; several concepts from the point of view of energy efficiency were implemented in the house. The following points summarize the energy-efficient concepts used for the house design to improve its thermal performance and reduce the energy consumption:

1- The house was built on north-south direction, with an open space at south to increase the south facade area, exposed to the sun in winter.

2- The glazing area of the southern facade was maximized, while the windows on the other facades were reduced. This approach was used by the designer to reduce the heating loads by increasing the solar gains from the south and reducing the heat loss from the other facades. Furthermore, sun-shading for the western facade is installed to reduce the overheating during the summer season.

3- The house has a compacted shape to minimize the exposed area of exterior walls to the cold climate and consequently to reduce the heat loss from the inside environment to the outside.

4- The day-used spaces such as reception, dining room and kitchen were arranged to the south facade to benefit from the period of sunshine in winter, while the night-used spaces such as the bedrooms were directed to northward.

5- The design of the envelope was based on increasing the house airtightness by using a continuous air barrier and improving the thermal resistance of the envelope by increasing the thermal insulation.

An Integrated Mechanical System (IMS) including water-to-air and water-to-water pumps and a geothermal coil were installed in the ground below the basement slab. The geothermal coil was expected to extract heat from ground in winter for domestic water and spaces heating and to reject heat to ground in summer. Although the IMS was installed at the house, it did not operate during the house monitoring due to malfunctions; therefore the impact of the system on the energy consumption is not included.

3.2 BLAST simulation program

The Building Loads Analysis and System Thermodynamics (BLAST) is a comprehensive program for predicting the energy performance of buildings. BLAST is extensively used to optimize the energy consumption of new or retrofit building design of different types and sizes. Since the repeated use of BLAST is inexpensive, it can be used to evaluate, modify and re-evaluate the design alternatives based on annual energy consumption. The program has its own user-oriented input language and is accompanied by a library, which contains the properties of most of materials, walls, roof and floor sections, listed in the ASHRAE Fundamentals Handbook.

Furthermore, the execution time of BLAST is brief enough to allow many alternatives to be simulated and the performance compared. The high flexibility of the input language makes BLAST a simulation environment, rather than a simple calculation software. Due to its high performance in modeling, the loads block of BLAST, which calculates the space thermal loads was selected to be implemented in the Energy Plus program, which is representative of the new generation energy analysis programs.

3.2.1 BLAST program algorithm

The heat balance method (ASHRAE Fundamentals Handbook, 1993) allows the instantaneous sensible heating load to be calculated. A heat balance equation is written for each enclosing surface, plus one for the room air. This set of equations is then solved for the unknown temperature of each inside surface and zone air temperature. Figure 3.9 (Pedersen *et al.* 1997) illustrates the heat balance process.

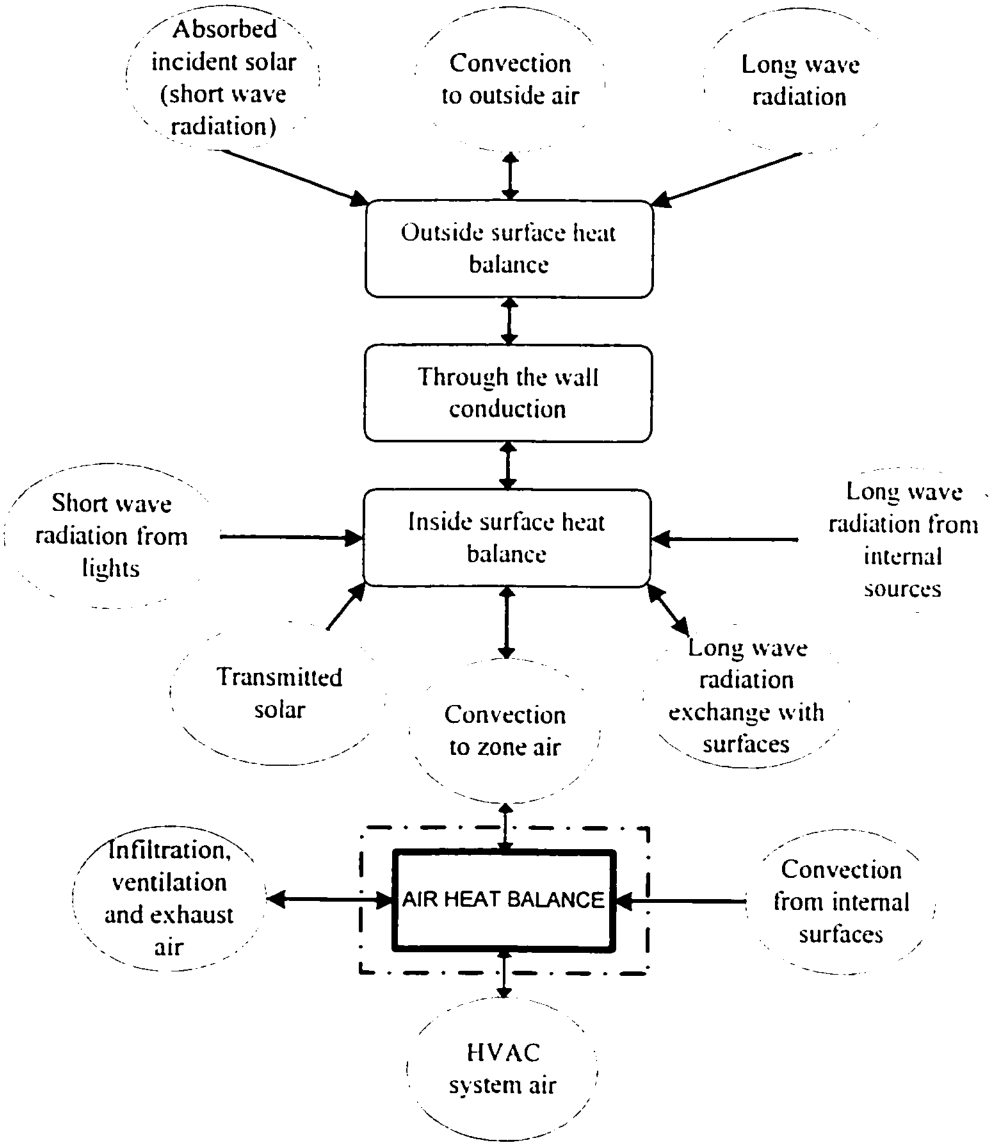


Figure 3.9. Schematic of heat balance process in a zone

The description of heat balance model (Pedersen, C. *et. al.* 1997) includes a description of the following four aspects: (i) outside surface heat balance; (ii) wall conduction process; (iii) inside surface heat balance; and (iv) air heat balance. The calculations are based on the following assumptions for each surface:

- Uniform surface temperature;
- Uniform longwave and shortwave irradiation;
- Diffuse radiating surfaces; and
- One-dimensional heat conduction within walls/ roof.

Outside surface heat balance

The heat balance on the outside face of each surface is expressed as following:

$$q_{asol} + q_{LWR} + q_{co} - q_{ko} = 0 \tag{3.2}$$

where:

q_{asol} = absorbed direct and diffuse solar radiation flux [W/m^2];

q_{LWR} = net longwave radiation flux exchanged with the surroundings [W/m^2];

q_{co} = convective flux with outside air [W/m^2]; and

q_{ko} = conductive heat flux through the wall [W/m^2].

Wall conduction process

For the heat balance process, the wall conduction process is formulated using the Conduction Transfer Functions (CTF). These functions relate the current conductive heat flux to the current and past surface temperatures; and the past conductive heat flux. The general form for the heat flux at the inside surface is:

$$q_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q_{ki,t-j\delta} \tag{3.3}$$

The general form for the heat flux at the outside surface is:

$$q_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q_{ko,t-j\delta} \tag{3.4}$$

where:

q_{ki} = conductive heat flux at inside face of the wall [W/m^2];

q_{ko} = conductive heat flux at outside face of the wall [W/m^2];

X_j, Y_j, Z_j, Φ_j = the Conductive Transfer Function (CTF) coefficients, where $j = 0,1,...nz$ [W/m^2.^{o}C];

T_i = inside face temperature [^{o}C]; and

T_o = outside face temperature [^{o}C].

δ = time interval [hour]

Inside surface heat balance

The inside face heat balance for each surface is expressed by the following formula:

$$q_{LWX} + q_{SW} + q_{LWS} + q_{ki} + q_{sol} + q_{ci} = 0 \tag{3.5}$$

where:

q_{LWX} = net longwave radiant exchange flux between zone surfaces [W/m^2];

q_{SW} = net shortwave radiant flux from lights to surface [W/m^2];

q_{LWS} = longwave radiation flux from equipments in the zone [W/m^2];

q_{ki} = conductive heat flux through the wall [W/m^2];

q_{sol} = transmitted solar radiation flux absorbed at surface [W/m^2]; and

q_{ci} = convective heat flux to zone air [W/m^2].

Air heat balance

There are four contributors to the air heat balance: (i) convection from the zone surfaces; (ii) convection of the internal loads; (iii) infiltration and ventilation; and (iv) the HVAC system. The formula for the air heat balance is:

$$\dot{q}_{conv} + \dot{q}_{CE} + \dot{q}_{IV} + \dot{q}_{sys} = 0 \tag{3.6}$$

where:

$\dot{q}_{conv}$ = convective heat transfer from surfaces to the zone air [W];

$\dot{q}_{CE}$ = convection of the internal loads [W];

$\dot{q}_{IV}$ = sensible load due to infiltration and ventilation air [W]; and

$\dot{q}_{sys}$ = heat supplied or extracted from the zone by the HVAC system [W].

It is assumed that the air temperature in the zone is uniform, and therefore the indoor air is represented as a single node. The electric baseboard heaters are the HVAC devices used in this study, as they were the only source for heating in the house.

Heat balance equations

As an example, let us assume a thermal zone with six surfaces (floor, ceiling and four walls). The unknowns are: the six inside face temperatures, the six outside face temperatures, and zone air temperature at each of the 24 hours. The subscript i is assigned as the surface index while the subscript j is assigned as the hour index, where:

$T_{so_{i,j}}$ = outside face temperature [^{0}C] for surface i = 1, 2, ... 6 and time j = 1, 2, ... 24;

$T_{si_{i,j}}$ = inside face temperature [^{0}C] for surface i = 1, 2, ... 6 and time j = 1, 2, ... 24.

By combing equations (3.2) and (3.4) and solved for T_{so}, one can obtain 6 equations for each time step:

$$T_{so_{i,t}} = \left(\sum_{k=1}^{nz} T_{si_{i,t-k}} Y_{i,k} - \sum_{k=1}^{nz} T_{so_{i,t-k}} Z_{i,k} - \sum_{k=1}^{nq} \Phi_{i,k}\, q_{ko_{i,t-k}} + q_{asol_{i,t}} + q_{LWR_{i,t}} + T_{si_{i,t}} Y_{i,o} + T_o h_{co_{i,t}} \right) / \left(Z_{i,o} + h_{co_{i,t}} \right) \qquad (3.7)$$

where:

h_{co} = convection coefficient of the outside surface face [W/m^2.°C], calculated by using: $q_{co} = h_{co} (T_o - T_{so})$

Similarly, by combing equations (3.3) and (3.5) and solved for T_{si}, one can obtain 6 equations for each time step:

$$T_{si_{i,t}} = \left(T_{so_{i,t}} Y_{i,o} + \sum_{k=1}^{nz} T_{so_{i,t-k}} Y_{i,K} - \sum_{k=1}^{nz} T_{si_{i,t-k}} Z_{i,k} + \sum_{k=1}^{nq} \Phi_{i,k}\, q_{ki_{i,t-k}} + T_{a_t} h_{ci} + q_{LWS} + q_{LWX} + q_{SW} + q_{sol} \right) / \left(Z_{i,o} + h_{ci} \right) \qquad (3.8)$$

where:

h_{ci} = convection coefficient of the inside surface face [W/m^2.°C], calculated by using: $q_{ci} = h_{ci} (T_a - T_{si})$

As shown in formula 3.8, there are three unknown variables for each surface: (i) the inside face temperature T_{si}; (ii) the outside face temperature T_{so}; and (iii) the zone air temperature T_a.

Substituting equation 3.7 in equation 3.8 results in one equation for each wall, hence six equations for the zone surfaces with seven unknowns: six inside face temperature T_{si} plus the zone air temperature T_a. The six equations are solved simultaneously along with equation 3.6; hence there are seven equations with seven unknowns. In the first evaluation, there is no heat input through the baseboard heaters to the zone.

The estimated value of the zone air temperature T_a is then compared with the required air temperature set by the control profile T_{cont}. If the zone air temperature is greater than the required temperature ($T_a > T_{cont}$), then no heating is required. On the other hand, if the zone air temperature is less than the required temperature ($T_a < T_{cont}$), then heating is required. The indoor air temperature is set equal to T_{cont}, and the set of seven equations is solved again to calculate the heat added by the baseboard heaters to the zone.

Similarly, the previous equation can be repeated for each zone of the building yielding the total energy consumption of the house.

3.2.2 BLAST program structure

The input file of BLAST consists of four sections, defined further below: (i) lead input, (ii) building description, (iii) fan system description, and (iv) central plant description. Figure 3.10 presents the hierarchy of the BLAST program.

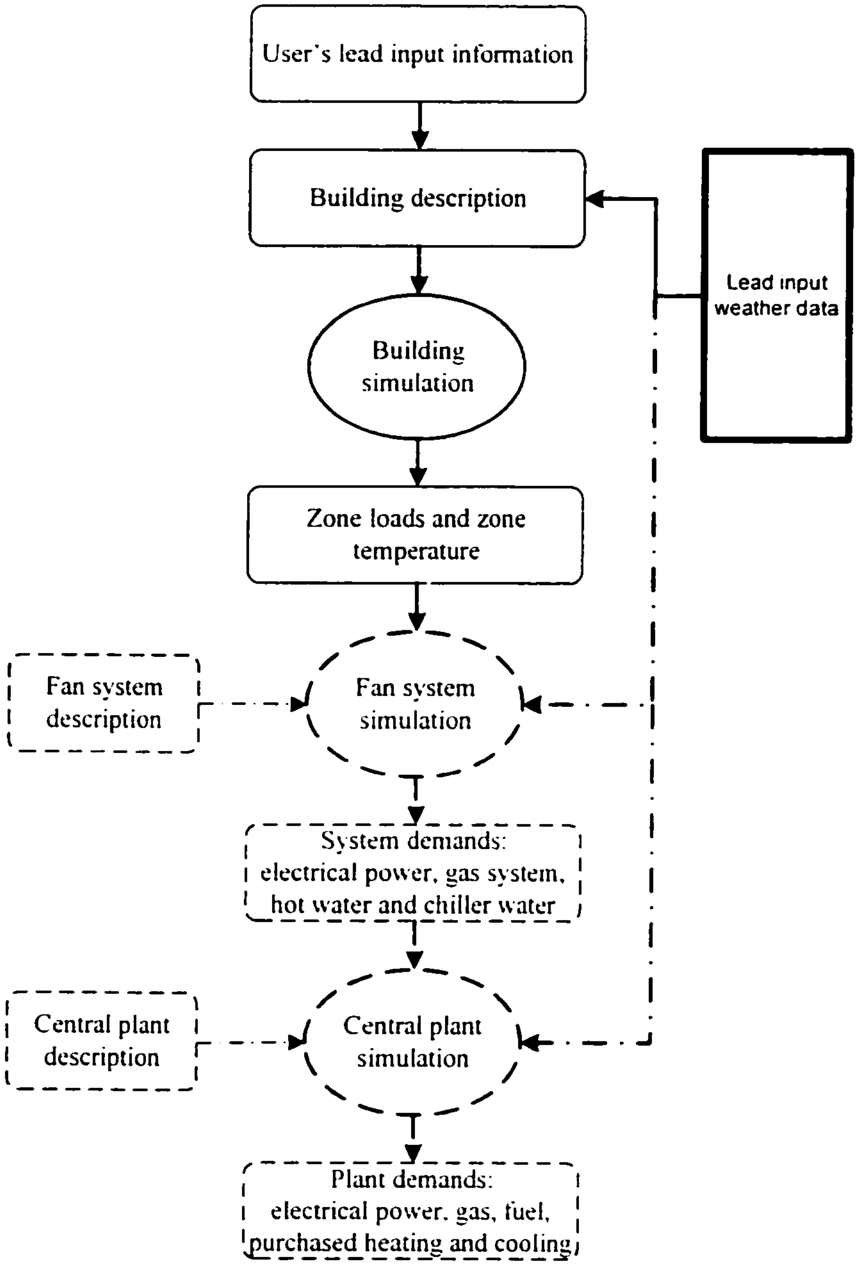


Figure 3.10. Hierarchy of BLAST program

Based on the lead input and building description sections, the simulation of each thermal zone is performed, evaluating the heating load of zones. The simulations for fan system and central plant can be implemented using the computed space loads, weather data and user inputs describing the building air handling system and central plant.

However, since the electric baseboard heaters are the only source of heating in the house, the fan system and central plant are not used in this study.

Lead input section

The lead input section of BLAST comprises the global information and materials characteristics of the Ray-Vision house. The global information includes information of latitude, longitude, house direction, and the temperature control profile. Although the materials characteristics can be extracted form the BLAST library in this study, they were explicitly defined and inserted in the lead input file. Material characteristics for the components of the walls, floors, roof, windows and doors were defined by using the information of the house description and the relevant materials properties, derived from ASHRAE Fundamentals Handbook (1997).

The massive walls such as concrete walls were defined by using the material thickness, L (m): conductivity, K (W/m-°C): specific heat, CP (kJ/kg-°C): density, D (kg/m^3), absorptivity coefficient for solar radiation, ABS: absorptivity coefficient for thermal radiation, TABS; and material roughness. For instance, the concrete used for concrete walls of the basement was defined by using the following term:

Concrete= (L= 0.25, K= 0.79, CP= 0.9, D= 1600, ABS= 0.9, TABS= 0.9, medium rough)

On the other hand, the lightweight materials, such as thermal insulation were defined by using the thermal resistance of such materials. Windows and transparent materials were defined using the thermal resistance R ($W/m^2 \cdot {}^{\circ}C$) and the shading coefficient.

Similarly, all house materials were defined, and then the house walls, partitions, floors and roof were defined in the BLAST input file by combining the relevant materials.

Building description

The house was divided into 14 thermal zones, as described before, including the basement, the ground and first floors and the attic. Each surface surrounding a thermal zone is described in one BLAST input file by the following set of variables:

1- Surface origin, which is the lower-left hand point of a surface;

2- Azimuth angle between the normal to the surface and north direction of the building;

3- Surface area;

4- Tilt angle;

5- Materials components or assembly;

6- The control profile including thermostat setpoint temperature and operating schedule;

7- Natural infiltration rate for each zone calculated in air change per hour at 4 Pa.

The blower door results revealed 1.25 ach at 50 Pa for the house (Chapter 4). From this value measured at 50 Pa pressure difference, the natural infiltration rate at 4 Pa was calculated (Lawrence Berkeley National laboratory, 1999): 1.25/20 = 0.0625 ach. To get the natural infiltration rate for each thermal zone of the house, the value of 0.0625 ach was divided by the area of northern and western facades, assuming that the infiltration is due to the prevailing wind in Montreal from north and north-west directions. Multiplying the natural infiltration per unit area (ach/m^2) of northern and western facades by the contribution area of each zone for these facades yielded the infiltration rate for zones.

However, these calculations were repeated assuming equal natural infiltration from all the house exterior surfaces including the attic. Simulation results indicated that the total energy consumption was almost equal for both methods of calculations with a variation of 10 kWh. The difference between these methods was only for the energy consumption calculated for each thermal zone.

A sample of the input file of the computer model is presented in Appendix A. In the present study, the BLAST program was used to analyze the energy consumption for heating of the base case house during the winter season starting from October 1st till April 30th. The heating load during the winter is the scope of this study. The preliminary computer model for the house was established by using the house drawings; the simulation results revealed that the energy consumption for heating was 11400 kWh. The calibration of the computer model with measurements and utility bills was performed and is presented in chapter 4.

CHAPTER 4

ENERGY PERFORMANCE MONITORING AND COMPUTER MODEL CALIBRATION

The computer model of the base case house was developed using the BLAST program and based on the on-site measurements such as air leakage from the blower door test and short-term monitoring of the indoor air temperature and electricity consumption. This chapter presents the measurements performed in the base case house, the monitored and estimated annual energy consumption and the approach used for the calibration of the computer model.

4.1 Building monitoring and measurements

Building monitoring was the essential technique used to collect actual information about the thermal behavior and energy performance of the base case house; this information is also used to develop and then calibrate the computer model of the house by comparing the results of simulation with the monitored energy consumption. The following data were collected:

- On-site measurements
- House operating conditions
- Utility bills

4.1.1 On-site measurements

The following tasks were performed: (i) the measurements of the airtightness using the blower door test and (ii) the measurements of the indoor air temperature of relevant spaces.

Blower door test

The Blower Door is a diagnostic tool designed to provide overall information about the building airtightness including the air leakage expressed as air change per hour (ach) at the standard pressure difference of 50 Pa between the outdoor and indoor (Canadian General Standards Board, 1986). The blower door consists of a powerful variable speed fan that is sealed into an exterior doorway and is used to blow air into or out of the house. When air is blown out of the house, it causes a negative pressure in the house relative to outside. This negative pressure induces outside air to enter the house through cracks or holes found in any exterior surface.

At the Ray-Vision house the fan was mounted on the exterior door, as shown in figure 4.1 at the ground floor. The mechanical system and electrical appliances were shut down and all windows and doors in the house were closed to ensure that the results were only due to the uncontrolled infiltration through the envelope. The control of the fan speed to maintain the selected level of pressure difference between outside and inside and the monitoring of the corresponding airflow rate was managed by utilizing the Automated Performance Testing system (The Energy Conservatory, 1998).

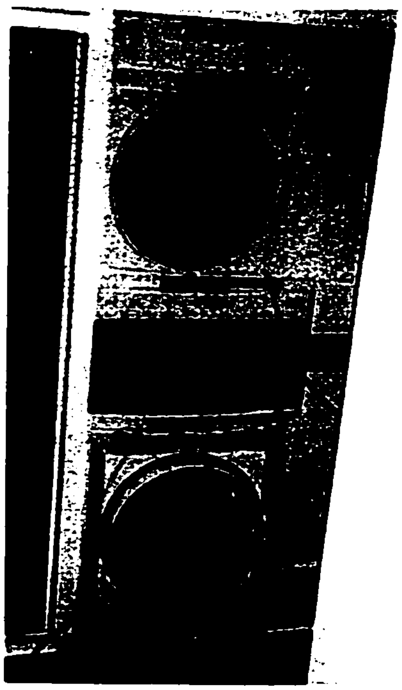


Figure 4.1. Blower door fan installed in doorway of the base case house

At the beginning, the blower door fan was turned on and its speed was increased until the pressure difference ΔP reached the upper target value of 50 Pa; then the automated system took a number of simultaneous measurements for different pressure differential, ΔP and fan flow rates, Q. The results included 300 measurements at each preset value of ΔP. Only the average values were presented, which allowed for the elimination of the variation due to wind changes in intensity and direction. The average value of all samples for that target pressure was displayed on the computer screen, on a graphic of $Q = f(\Delta P)$. The fan speed was then automatically reduced until the pressure difference reached the next target pressure of 40 Pa, and data were collected again. A second point, corresponding to the averaged measured values around 40 Pa, was displayed on the screen. The process was repeated by decreasing every time the ΔP by about 5 Pa down to about 10 Pa.

At the end of the measurements, a number of points (Q, ΔP) was obtained, from which the air leakage was determined. The relation between the infiltration rate Q and pressure difference ΔP is expressed by:

$$Q = C * (\Delta P)^n \tag{4.1}$$

where:

Q = air flow rate [L/s];

ΔP = pressure difference between the outside and inside of the house [Pa];

C = flow coefficient [$L/(s \cdot Pa^n)$]; and

n = flow exponent.

The power law (equation 4.1) is converted into the linear model as follows:

$$\mathrm{Log}\,(Q) = \log\,(C) + n * \log\,(\Delta P) \tag{4.2}$$

Assuming that $\log(Q) = Y$; $\log(C) = g$, and $\log(\Delta P) = X$, then

$$Y = g + n\,X \tag{4.3}$$

Using the least square method applied to the set of points (Q, ΔP), the coefficients g and n were obtained, which led to the coefficients C and n. These calculations were automatically performed by the Automated Performance Testing system. Figure 4.2 illustrates the relation between X and Y, as presented by the automated system. The values of constants C and n were evaluated to be 6.2 and 1.0, respectively. The accuracy of C and n was ± 18.8% and ± 0.051% respectively.

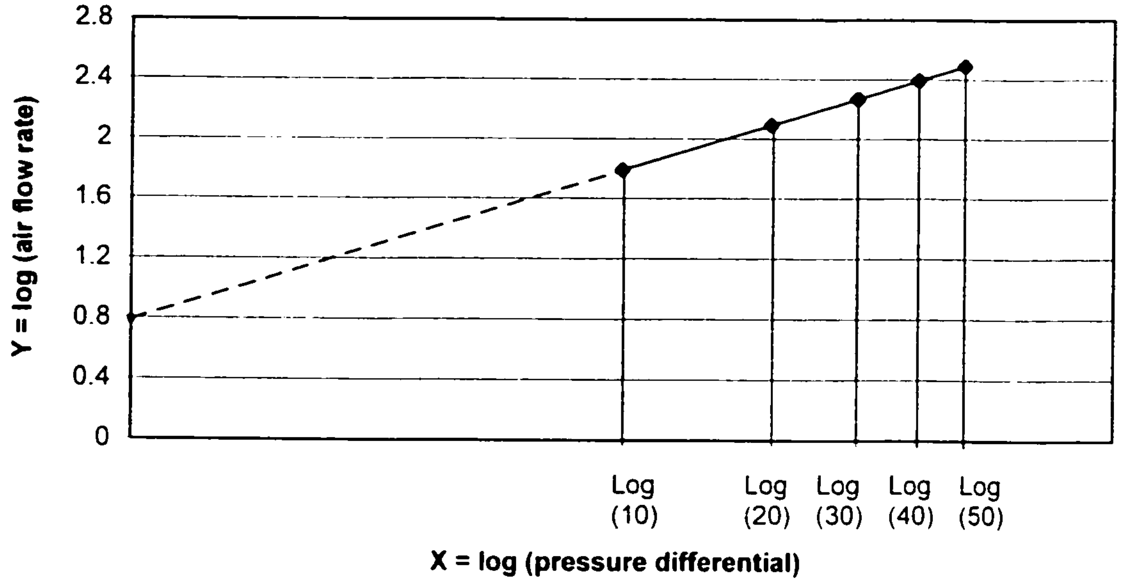


Figure 4.2. Correlation between the fan flow rate and the pressure differential

Substituting the constant values of C and n in formula (4.1), then the airflow Q_{50} through the fan at 50 Pa was evaluated. The air change per hour was calculated by applying the flowing formula:

$$\text{Air change per hour [ach]} = (Q_{50} * 3.6)/ V_{house} \qquad (4.4)$$

where:

V_{house} = the volume of the house [m^3].

The results revealed 1.25 air change per hour at 50 Pa with accuracy of ± 1.1%. For comparison purposes, a new well-built house has commonly between 3 and 4 ach (Zmeureanu, R. 2000), while the R-2000 energy-efficient house (built according to specifications developed by Natural Resources Canada) must not exceed 1.5 ach. Therefore this house has a higher airtightness than most energy-efficient houses.

Indoor air temperature

Indoor air temperature was measured by using data loggers. The data logger (Figure 4.3) has many features to collect data from both the electrical current and the ambient temperature. It consists of a current-monitoring channel and an internal thermistor temperature channel to measure the temperature. The internal temperature sensor has accuracy of ± 0.7°C at 25°C. The loggers were installed in the basement and ground floors at the center of the living room and bedrooms to monitor the indoor air temperature for one week. The measurements were performed every 8 seconds and averaged over 32 seconds; the average data was saved. Data was extracted from the loggers by using the TrendReader software program (1994) and transferred to the EXCEL spreadsheet program. The hourly average air temperature was then calculated from the measurements with a time-step of 32-second. These hourly values were used to calibrate the computer model by comparing with the simulation results.

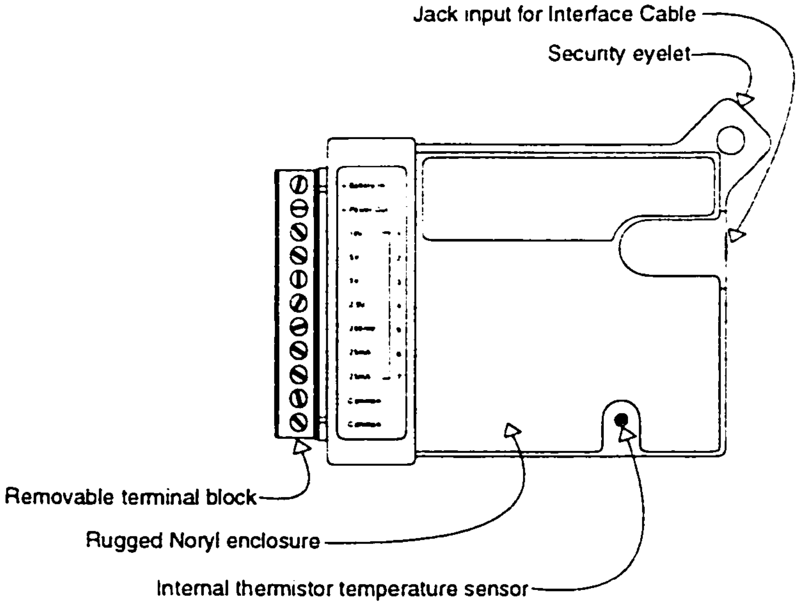


Figure 4.3. Components of the data logger

4.1.2 House operating conditions

The information about the house operating conditions was collected through discussions with the house occupants. Although some researchers neglect the life style and the occupants energy-related behavior, sometimes it has a major effect on the building performance. The base case is a duplex house, which is occupied by two families, the owner family at the basement and ground floor and the tenant family on the second floor.

Several points were mentioned by the owner and have major impacts on the house thermal performance:

1- The newly installed mechanical and ventilation system was out of order due to some manufacturing problems. The heating was provided through the electrical baseboards, so that electricity is the only source of energy used in this house.

2- Since the owner family rarely used the basement, they adjusted the thermostat at a very low setpoint temperature of about 10°C to reduce the energy consumption.

3- The owner recorded himself and provided the hourly thermostat setpoints, used on the ground floor from January 30th till February 5th. It was observed that the average heating setpoints were approximately 15°C at night (from 10:00 PM till 8:00 AM) and 21°C by day (from 8:00 AM till 10:00 PM). Figure 4.4 illustrates the recorded data by the owner along with the variations of the thermostat-operating schedule.

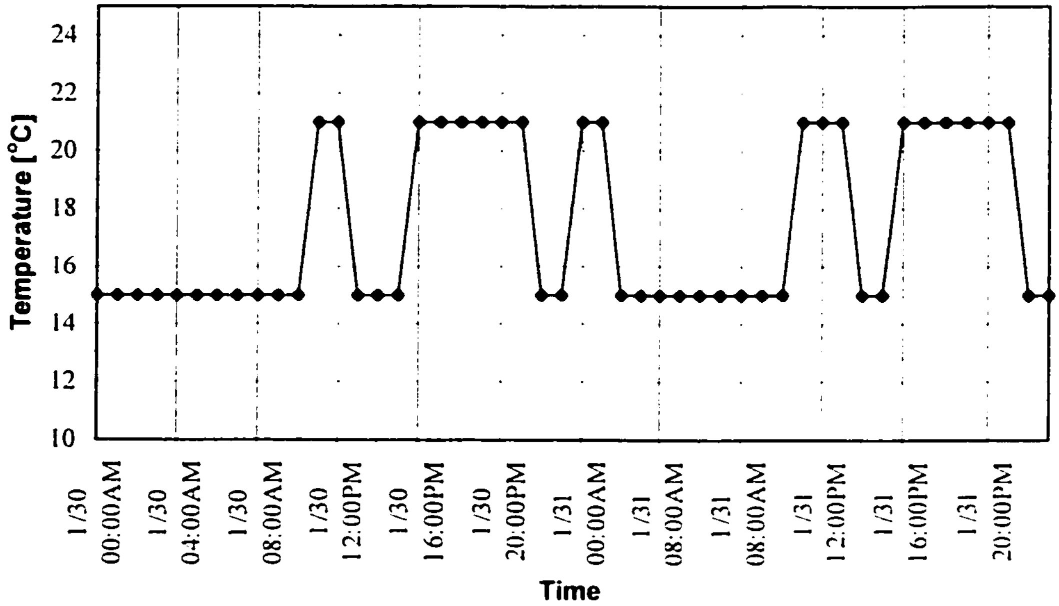


Figure 4.4. Owner control profile

4.1.3 Analysis of utility bills

The information used to evaluate the actual energy consumption of the base case house was extracted from the utility bills over a twelve-month period from June 14. 2000 till June 14, 2001. The analysis of utility bills for one-year period enabled the comparison of the monitored results with the simulation results from BLAST and therefore helped with the model calibration. The base case house consists of two apartments with two installed electrical meters, one for each apartment; therefore two different bills are issued for the entire house. As mentioned before, the installed mechanical system responsible for ventilation, heating and cooling was out of order and the heating was provided through the electric baseboards during the winter. Therefore the electricity consumption was only due to the heating, domestic hot water, cooking, lighting and electrical appliances. Table 4.1 illustrates the actual energy consumption of the house, extracted from utility bills between June 14, 2000 and June 14, 2001.

Table 4.1. Data extracted from the utility bills

Date	Number of days	Energy Consumption [kWh]		
		Ground and basement	Second floor	Total of the house
Jun 14 to Aug 16	63	1250	1290	2540
Aug 16 to Oct 17	62	1260	1280	2540
Oct 17 to Dec 13	57	1820	1810	3630
Dec 13 to Feb 13	62	2870	2760	5630
Feb 13 to Apr 24	70	2010	2530	4540
Apr 24 to Jun 14	51	990	1450	2440
Total	365			21320

The information collected from the utility bills revealed that the total energy consumption of the base case was 21320 kWh per year. The heated floor area of the house is approximately 310 m^2 composed of 105.78 m^2 for basement; 103.28 m^2 for ground floor; and 100.47 m^2 for the second floor. The yearly energy consumption per square meter for the base case is evaluated at 68.89 kWh/(m^2·yr).

By analyzing the information, presented in table 4.1, it was noticed that the annual energy consumption of the tenant's apartment of 100.47 m^2 exceeded the energy consumption of owner's apartment of 209 m^2. This result is partially due to the basement operating conditions. Since the basement was rarely used and its thermostat setpoint was set at about 10°C, the energy consumption of the basement is considerably low. Consequently, since the basement is practically not heated, the area of the basement was excluded from further calculations of the index of energy performance (kWh/(m^2·yr)). Another part of explanation is that the second floor has one more exterior surface (the roof) for heat loss than the ground floor.

The energy consumption, extracted form the utility bills, was divided only by the floor area of ground and second floors. Thus, the unit annual energy consumption of the house is 104 kWh/(m^2·yr). This house is more energy-efficient than the average houses built after 1990 in Montreal with an annual energy consumption of 124 kWh/(m^2·yr) (Zmeureanu, R. 2000).

4.2 Computer model calibration

The computer model was built by using the BLAST program to simulate the thermal performance of the base case. Only the heating season was simulated from October 1st till April 30th. The calibration of the computer model is an essential part to obtain reliable results. The calibrated model will further be used to estimate the energy performance of selected design alternatives, applied to the base case house.

4.2.1 Actual energy consumption for heating

This research focuses on the thermal performance of the house during winter, so that the heating consumption during this period is the main interest. From the utility bills, the yearly energy consumption can be divided into two categories: (i) the heating consumption during the winter season, and (ii) the base load of electricity consumption including domestic hot water, cooking, lighting and electrical appliances consumption. Data collected from utility bills revealed that the energy consumption of the period June 14 to August 16, 2000 (2 months) was equal to that of the period from August 16 till October 17, 2000 (2 months), and close enough to that of the period from April 24 to June 14, 2001.

These periods were considered as non-heating season whereas the heating consumption was not required. Given the energy consumption from October to April, the base load was assumed to be constant for the entire year to simplify the heating consumption calculations; therefore the energy consumption during the summer was considered only for the base load. Calculating the average base load during the period from June 14 till October 17, and deducting it from the energy consumption during the heating season led to the heating consumption for each period. Table 4.2 illustrates the total heating consumption from October 17, 2000 till April 24, 2001 as calculated from the utility bills using the assumption of constant base load throughout the year. Results show that the heating consumption is evaluated at 6118 kWh.

Table 4.2. Heating consumption of the base case house

Date	Number of days	Energy consumption [kWh]		
		Ground and basement	Second floor	Total of the house
Jun 14 to Aug 16	63	0.0	0.0	0.0
Aug 16 to Oct 17	62	0.0	0.0	0.0
Oct 17 to Dec 13	57	675	638	1313
Dec 13 to Feb 13	62	1625	1485	3110
Feb 13 to Apr 24	70	605	1090	1695
Apr 24 to Jun 14	51	0.0	0.0	0.0
Total	365			6118

4.2.2 Simulation Results and Comparisons

The initial computer model of the base case was established by using the house drawings and specifications, as described in chapter 3. The simulation results for the yearly heating consumption were estimated at 11400 kWh for the winter period from October 1st till April 30th. There was much difference between the model simulation results of 11400 kWh and the heating consumption of 6118 kWh, extracted from the utility bills and presented in table 4.2. A detailed review of the model-input data and the analysis of the house measurements were performed. The difference between results were due to:

1- Basement operating conditions. The owner stated that the basement was rarely used, and the thermostat was continuously adjusted at 10°C, which is lower than the temperature of the ground floor (21°C at day and 15°C at night). In the initial computer model, the basement was assumed to be a heated space at the same thermostat setpoint of that at the ground and second floors, which was estimated at 22°C at day and 19°C during the night.

2- Difference between the thermostat setpoint temperatures of the base case (ground and second floors) and the computer model. The owner set the thermostat at 21°C at day and 15°C at night, while the initial computer model used 22°C and 19°C, for the day and night, respectively.

3- Due to the issued dates of utility bills, the heating periods were estimated to be from October 17 till April 24, while the simulated heating periods were from October 1 till April 30. Although the simulated heating consumption from October 1 till October 17 and from April 24 till April 30 is low, it has impact on the simulation results.

4- Although two families live in the base case house, one at the ground floor and the other on the second floor, the number of people was not considered at the initial computer model, so that the latent and sensible loads for people, which may affected at the computer model performance were not calculated.

Modifications of the computer model

Based on the above observations, the BLAST input file was revised, and the following modifications were applied to the computer model to improve its performance:

- Basement control profile

The basement thermostat set point was set at (1 at 8°C - 0 at 10°C) with a constant schedule for 24 hours. This profile indicates that the heating system is turned on, if the basement air temperature is equal to or drops below 8°C, and is turned off when is 10°C or higher.

- Control profile for the ground and second floors

The initial control profile was (1 at 20°C - 0 at 22°C) during the day and (1 at 17°C - 0 at 19°C) at night. Following the owner explanation, the profile was modified to be (1 at 20°C - 0 at 21°C) during the day and (1 at 14°C - 0 at 15°C) at night. These modifications were applied to both the owner and tenant apartments.

- People

The number of occupants was not considered at the initial computer model. A family with 4 persons was added to each apartment. The people schedule and activity levels were applied as well to express the actual life style of the occupants.

Comparisons between simulation and monitoring results

The comparisons between the simulated and monitored results of heating consumption and indoor air temperature are established and displayed as follows:

Heating consumption

By applying the previous modifications to the computer model and performing the simulation by using the BLAST program for the same period of utility bills from 17 October till 24 April, the heating consumption of the base case house was estimated at 6983 kWh. Comparison between the simulated and actual heating consumption is shown in table 4.3:

Table 4.3. Actual and model heating consumption

Date	Number of days	Energy consumption [kWh]		
		Computer model	Actual	Difference
Oct 17 to Dec 13	57	1743	1313	430
Dec 13 to Feb 13	62	3114	3110	4
Feb 13 to Apr 24	70	2126	1695	431
Total	189	6983	6118	865

From table 4.3, the difference between the simulation results of the base case and the heating consumption derived from electricity bills was 865 kWh or approximately 14% of the actual heating load of the house in the winter. Differences between 10% to 18% of the simulation and actual results are generally accepted by researchers; for instance Zmeureanu *et al.* (1995) and Burch *et al.*(1986).

The difference between the estimates of the heating consumption obtained from the modified computer model and the heating consumption, calculated form the utility bills was due to the following reasons:

- The difference between the weather file data of BLAST program, created in year 1990 for the city of Montreal, and the actual weather temperature for year 2000-2001. The weather temperature of year 1990 was lower than the actual temperature in year 2000, which indicates the increase of heating consumption, as estimated by the computer model. For instance, the average temperature for October was 7.8°C in the BLAST weather file, while it was 9.12°C in year 2000, as measured by Environmental Canada at Dorval airport.

- The uncertainty of the house operating conditions, as it was uncertain that the occupants used the heating system during October or April months. The simulation results for heating consumption were from October 17 till April 24, which may indicate more heating load for the model than the actual heating consumption in the October and April months.

- Since the information used to build the program input file was obtained from the drawings sheets and specifications of the house, there may have been a slight difference between the information included in the drawings and the actual house.

Indoor air temperature

By analyzing the owner control profile, it was noticed that the owner used lower thermostat setpoints than those used in most houses. The owner control and schedules were applied in the input file of computer model to have the same actual conditions of the house. Comparisons between the simulated indoor air temperature of the modified computer model, the short-term monitoring of the indoor air temperature and the owner profile of the thermostat setpoint temperature were performed.

Figures 4.5 and 4.6 illustrate: (i) the simulated air temperature in the living room, (ii) actual temperature and (iii) the owner setpoint temperature for the periods of February 2nd and February 3rd in year 2001.

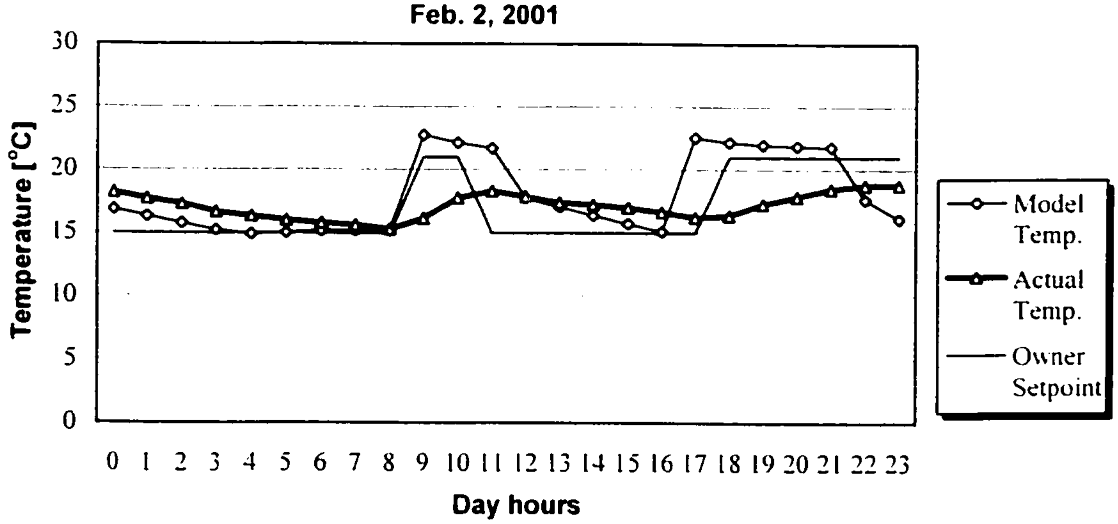


Figure 4.5. Simulated and actual indoor air temperature for Feb.2

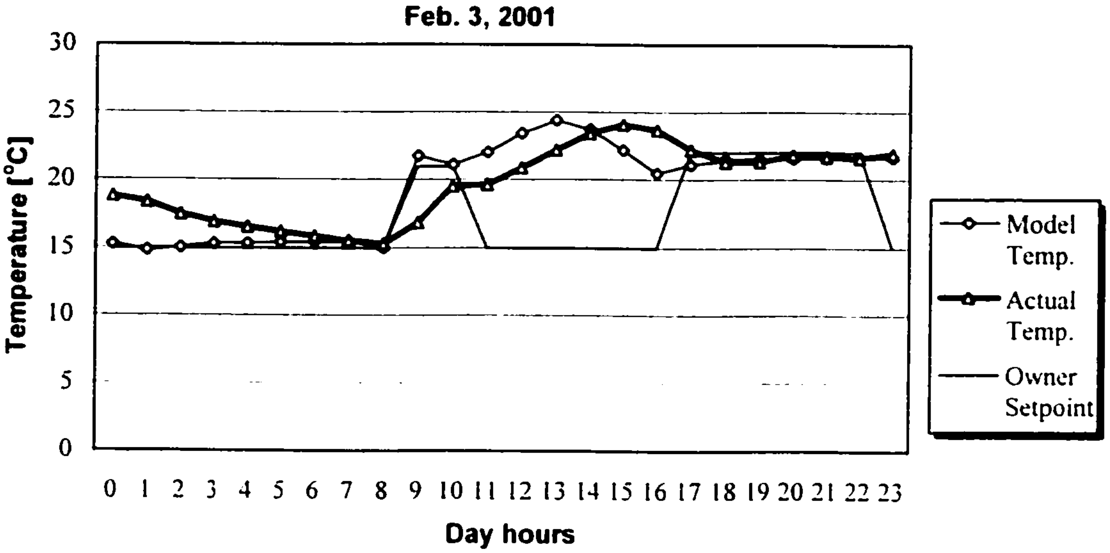


Figure 4.6. Simulated and actual indoor air temperature for Feb.3

Comparing the results issued from the previous figures, there was a slight difference between the model temperature and monitored temperature, however both have approximately the same shape of variations, which indicates the model gives reasonable results. The model temperature profile almost follows the owner setpoint profile, while there is a small difference between the actual temperature and the owner setpoint temperature. This difference is due to the uncertainty of occupants behavior, and the inaccuracy of the owner control profile that was reported to us. It was interesting to observe that the difference between the model and measured temperatures and owner setpoint temperature, as shown in figure 4.6 was due to the solar radiation penetrated in the living room through the large bay windows at noon. In spite of the uncertainty of the owner control, it was the only estimated control profile that can be applied to the input file of the computer model to present the real house operating conditions.

4.2.3 Final computer model

The results show that the modified computer model estimates the annual heating energy consumption within 14% of the monitored values. These results indicate the computer model is representative for the Ray-Vision house. In this section, the last computer model is modified again to be more representative to the operating conditions of most houses. Two modifications were applied to the calibrated computer model to establish the final computer model:

1- Modification of the control profile. A new control profile was established and applied to the entire house. The new control profile is (1 at 20°C – 0 at 22°C) during the day and (1 at 17°C – 0 at 19°C) at night. This profile indicates that the heating system is turned off at 22°C or higher, and is turned on at 20°C during the day, while the heating system is turned off at 19°C or higher, and is turned on at 17°C at night.

2- Modifications of the operating conditions of the basement. New control profile of (1 at 20°C – 0 at 22°C) during the day and (1 at 17°C – 0 at 19°C) at night for the basement was applied. In addition, the number of people and activities schedule was modified as well to express the usage pattern of the basement in recent houses.

The final computer model estimated the yearly heating consumption from October 1st till April 30th at 10470 kWh or 34 kWh/(m^2·yr). It should be noted that the basement area was accounted in the final computer model. This increase of heating load is due to the increase of the thermostat setpoint temperature for the entire house and the modifications of the basement operating conditions.

Figure 4.7 presents the monthly heating consumption of the final computer model for the base case house.

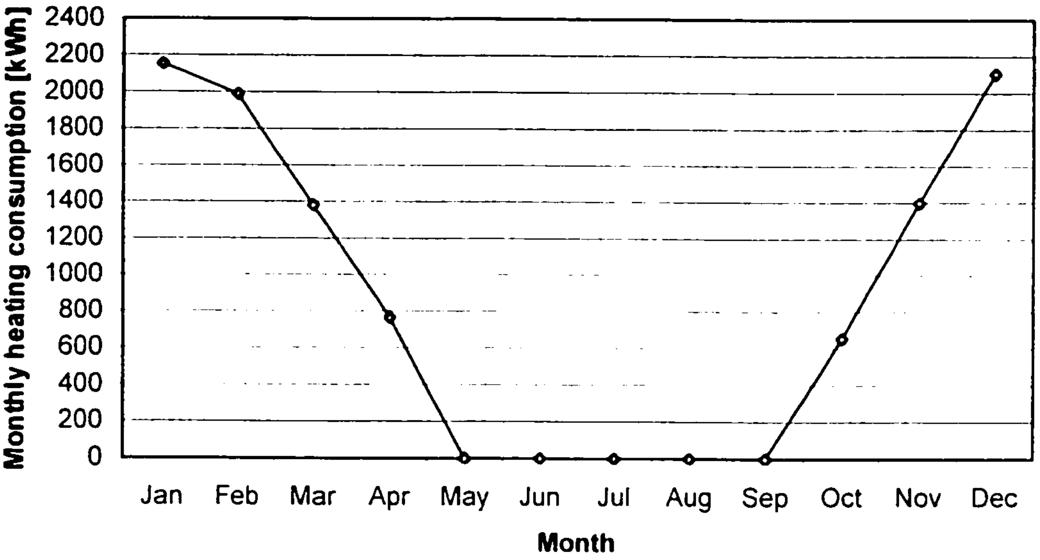


Figure 4.7. Monthly heating consumption of the final computer model

The final computer model, developed in this section, is used in the following chapters of this thesis as the base case computer model for evaluating the energy performance of selected design alternatives.

CHAPTER 5

ENERGY PERFORMANCE OF SELECTED BUILDING DESIGN ALTERNATIVES

In this chapter, several design alternatives are proposed to improve the thermal performance of the base case house. Two approaches were used to establish the design alternatives: (1) the parametric analysis approach, and (2) the non-parametric analysis approach. The parametric analysis approach comprises: (i) the modifications of the characteristics of building envelope, (ii) the modifications of the architectural design, and (iii) the modifications of the building operating conditions. On the other hand, the non-parametric analysis approach was used to propose innovative design concepts for the base case. The evaluation of the energy performance of the selected design alternatives were performed by using the BLAST program and the final calibrated computer model, described in chapter 4.

5.1 The parametric analysis approach

The parametric analysis approach is used to propose modifications, via the design parameters to the base case. Values of some building parameters, expected to have a considerable impact on the energy performance of the base case house were changed without changing the actual design approach, proposing several design alternatives for the base case. The design parameters were classified in the following categories:

1- Modifications of the characteristics of the building envelope including:
    - (i) thermal resistance of the exterior walls, roof and windows;
    - (ii) airtightness;
    - (iii) thermal mass of the interior and exterior walls;
    - (iv) solar absorptivity of the interior and exterior surfaces of wall; and
    - (v) installation of movable insulation on the interior side of windows.

2- Modifications of the architectural design comprising:
    - (i) building form;
    - (ii) glazing-to-wall ratio;
    - (iii) building orientation; and
    - (iv) presence of close or attached buildings.

3- Modifications of the thermostat setpoint temperature for heating.

For each generic alternative, five values were set for the representative parameter: a minimum value, a maximum value and three intermediate values. Hence, five design alternatives were created for each generic alternative. When one parameter was changed, the rest of design parameters held the values corresponding to the base case house. This approach allowed investigating the impact of each parameter on the energy consumption of the base case. By changing the input file of the base case model corresponding to the specific value of each parameter, new computer models were established for the proposed generic alternatives. Only the heating season was simulated from October 1st till April 30th.

5.1.1 Modifications of the characteristics of building envelope

It was not straightforward to establish the appropriate values for each design alternative based on the characteristics of the base case envelope. Therefore, a study was performed to select the most appropriate and available values for each alternative. The minimum and maximum values were usually derived from similar studies and the related regulations and specifications of Quebec.

The intermediate values were established by selecting the value of the base case and two other values between the minimum and maximum values. The rationale used to establish the design alternatives for each design parameter is explained in this chapter. Table 5.1 presents the values of the characteristics of the envelope of the base case house.

Table 5.1. Characteristics of the base case envelope

Base-case envelope parameters	value
Thermal resistance [$m^2 \cdot {}^oC/W$]:	
Basement walls	4.4
Above ground walls	5.4
Roof	10.87
Windows thermal resistance [$m^2 \cdot {}^oC/W$]	
Casement window	0.59
Fixed window	0.56
Infiltration [ach] at 50 Pa	1.25
Exterior wall masses [kg/m^2]:	
Basement walls	505
Above ground walls	320
Solar absorptivity coefficient of:	
External walls	0.75
Internal walls (gypsum board partitions)	0.75
Thermal resistance of movable insulation [$m^2 \cdot {}^oC/W$]	0.0

Variations of the thermal resistance of building envelope

Five values were set for each design alternative of the thermal resistance parameter of the three main building envelope assemblies: basement walls, above ground walls (ground and second floor walls) and the roof. The minimum value proposed for the thermal resistance of basement walls, above ground walls and the roof was 2.2 (R12.5), 3.4 (R19.3) and 5.3 (R30) $m^2 \cdot {}^oC/W$ respectively; these values comply the minimum requirements of Quebec regulations (1992). The maximum value of the thermal resistance was 8.8 (R50), 10.57 (R60) and 17.61 (R100) $m^2 \cdot {}^oC/W$ for the basement, above ground walls and the roof, respectively. These maximum values were selected based on a study of a hyper-insulated house in Saskatchewan, Canada (Dumont, R. 2000). Although higher values of thermal insulation were applied in the present study, they were not considered because: (i) the incremental cost of construction is extremely high due to the increase of thickness of the exterior wall, and (ii) the reduction of the energy consumption was found to be insignificant.

Three intermediate values including the base case thermal resistance value, were proposed and presented in table 5.2. As the thermal insulation is the dominant factor affecting the total thermal resistance of the building envelope, therefore increasing or decreasing the thermal insulation of the basement, above ground walls and the roof, proposed different design alternatives. Table 5.2 illustrates the simulation results of each alternative proposed for the thermal resistance parameter.

Table 5.2. Heating consumption of the thermal resistance alternatives for the envelope

Design alternatives	Thermal resistance [$m^2 \cdot °C/W$]	Heating consumption [kWh]	Reduction of heating consumption [%]
Basement walls:			
Alternative 1	2.2 (R12.5)	12 090	-15.5
Alternative 2	3.35 (R19)	10 990	-4.9
Alternative 3 (base case)	4.4 (R25)	10 470	0.0
Alternative 4	6.61 (R38)	9 986	+4.6
Alternative 5	8.8 (R50)	9 606	+8.3
Above ground walls:			
Alternative 6	3.4 (R19.3)	12 270	-17.2
Alternative 7	4.4 (R25)	11 170	-6.7
Alternative 8 (base case)	5.4 (R30)	10 470	0.0
Alternative 9	7.05 (R40)	9 751	+6.9
Alternative 10	10.57 (R60)	8 943	+14.6
Roof or attic:			
Alternative 11	5.3 (R30)	11 180	-6.8
Alternative 12	7.92 (R45)	10 720	-2.4
Alternative 13 (base case)	10.87 (R62)	10 470	0.0
Alternative 14	14.09 (R80)	10 300	+1.6
Alternative 15	17.6 (R100)	10 160	+3

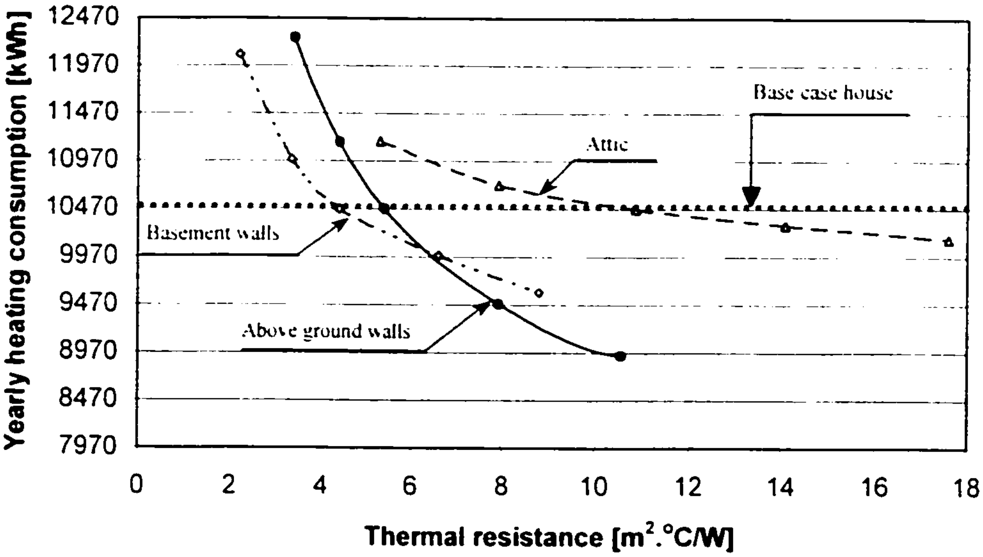


Figure 5.1. Yearly heating consumption versus thermal resistance of exterior envelope

From the results shown in table 5.2 and figure 5.1, it is noticed that there is a considerable variation of energy savings due to the increase of the thermal resistance values of the basement, above ground walls and the roof. Increasing the thermal resistance for the above ground walls would lead to a greater reduction of the heating consumption compared with the impact of thermal resistance of the basement walls and roof.

Other alternatives were proposed, as shown in table 5.3, by using the whole set of minimum, maximum and intermediate values. For instance, the alternative 1 (Table 5.3), uses the minimum thermal resistance values of 2.2, 3.4, 5.3 m^2·°C/W for the basement walls, above ground walls and the roof respectively.

Table 5.3. Total thermal resistance alternatives vs. heating consumption

Design alternatives	Thermal resistance [m^2·°C/W]	Heating consumption [kWh]	Reduction of heating consumption [%]
Basement walls, above ground walls and roof:			
Alternative 1 (minimum)	(2.2, 3.4, 5.3)	14 610	-39.5
Alternative 2	(3.35, 4.4, 7.92)	11 950	-14.1
Alternative 3 (base case)	(4.4, 5.4, 10.87)	10 470	0.0
Alternative 4	(6.61, 7.05, 14.09)	9 907	+13.1
Alternative 5 (maximum)	(8.8, 10.57, 17.61)	7 775	+25.7

From table 5.3, the use of the minimum value of thermal resistance (Alternative 1) would lead to the increase for heating consumption by 39.5% compared with base case, while the use of maximum insulation level (alternative 2) would lead to the decrease by 25.7%. These results indicated a significant impact of the thermal resistance of the entire building envelope on the energy performance of the base case house.

Variations of the thermal resistance of windows

Five values were proposed for the thermal resistance parameter for windows. The minimum thermal resistance for double-glazed windows of 0.36 m^2·°C/W is prescribed by the energy-related regulations of Quebec province. This value was assigned to the minimum value of this parameter. Triple-glazed windows with low emissivity coating and filled with argon gas with a total thermal resistance of 0.88 m^2·°C/W was proposed as the maximum value of this parameter. This value was selected based on the study of Dumont (2000). Three intermediate values were proposed as well for double-glazed windows with total thermal resistance of 0.49, 0.56 (base case) and 0.74 m^2·°C/W. The values of 0.49 and 0.74 m^2.°C/W were selected based on the study of energy-efficient windows (Wills, C. 2000).

By changing the thermal resistance of windows in the input file of the base case computer model, five computer models for the design alternatives were established. Table 5.4 presents the yearly energy consumption for heating with respect to the different values of thermal resistance of windows.

Table 5.4. Total thermal resistance of windows vs. heating consumption

Design alternatives	Thermal resistance [m^2·°C/W]	Heating consumption [kWh]	Reduction of heating consumption [%]
Alternative 1 (minimum value)	0.36	12 140	-16
Alternative 2	0.49	11 030	-5.4
Alternative 3 (base case)	0.56	10 470	0.0
Alternative 4	0.74	9 798	+6.4
Alternative 5 (maximum value)	0.88	9 366	+10.5

Results revealed an increase of heating consumption of about 16% whenever the minimum thermal resistance alternative was applied, namely alternative 1. A reduction of about 10.5% for the yearly energy consumption for heating was achieved, when triple-glazed windows were used. As the base case uses a high thermal resistance for windows of 0.56 $m^2.^oC/W$, it is expected that the impact of increasing the thermal resistance for windows at the energy consumption to be more significant in conventional houses.

Variations of the air infiltration rate

Infiltration is the uncontrolled inward air leakage through cracks and pathways of the building envelope, caused mainly by the effects of wind pressure and the difference of temperature between the inside and outside environment. The blower door test for the base case indicated that the air infiltration rate at 50 Pa was equal to 1.25 air change/ hour (ach). A literature search revealed that a new well-built house has commonly between 3 and 4 ach (Zmeureanu, R. 2000); so that the maximum value of the infiltration rate was set at 3 ach for the design alternatives. In the study of Advanced Canadian Houses (Hickling Corporation, 1993), the infiltration rate was between 0.9 and 1.5 ach at 50 Pa for most houses. The minimum value of the infiltration rate parameter was selected in this study to be 0.6 ach. Three intermediate values were proposed: 1.25 (base case), 1.8 and 2.4 ach. By changing the infiltration rate for the thermal zones of the base case to the modified values of the design alternatives, the computer models for the design alternatives were established. Figure 5.2 presents the heating consumption as result of the modification of the air infiltration rate.

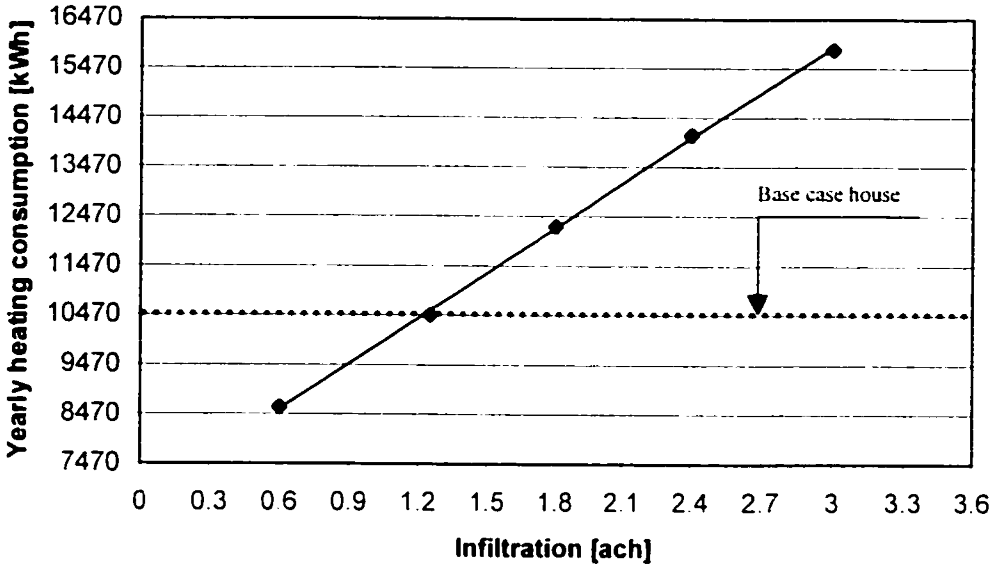


Figure 5.2. Yearly heating consumption versus air infiltration rate

Results from the previous figure revealed that the relationship between the air infiltration rates versus the yearly heating consumption followed a linear regime for the proposed alternatives, which indicates a significant impact of air infiltration rate at the energy consumption. There was an increase of heating consumption of about 17.5% whenever the infiltration rate increased by 0.6 ach.

For instance, there was an increase of heating consumption by 51.5% when the infiltration rate of 3 ach was used, compared with the base case. A reduction of 17.5% of heating consumption was noticed when the infiltration rate of 0.6 ach was used.

Variations of the thermal mass of the house envelope

The thermal mass for the basement and above ground walls includes: (i) exterior wall mass, where the thermal mass is installed on the cold side of the insulation; and (ii) interior wall mass, where the thermal mass is installed on the warm side of the insulation. The mass of walls [kg] was calculated by using the material density of building envelope [kg/m^3], based on data published in ASHRAE Fundamentals Handbook (1997); and the volume of such materials [m^3], extracted form the base case drawings and specifications. The mass of basement and above ground walls of the base case is 506 and 320 kg/m^2 respectively.

There were not specific values for optimum thermal mass of building walls, established from similar studies; therefore, five values of each of the basement walls and above ground walls were selected based on the thermal mass of base case. For instance, the external mass of basement walls was set to be 253, 506 (base case), 759, 1012 and 1265 kg/m^2; whereas it was 160, 320 (base case), 480, 640 and 800 kg/m^2 for the external mass of the above ground walls. These previous values have a percentage ratio of the thermal mass of the base case accounting 50%, 100% (base case), 150%, 200% and 250% respectively. By modifying the width of the concrete wall for the basement and the width of the brick for the above ground walls at the input file of base case computer model, then the volume and consequently the mass of such walls changed and the alternatives models were established. When the width of concrete or brick walls was modified, the thermal resistance of such walls would change as well.

In order to separate the impact of thermal mass on the energy performance of the base case, it was assumed that the thermal resistance of such walls would not change and took the same values of base case walls. Practically, different kinds of concrete components or bricks with different thermal resistance can be applied to maintain the same thermal resistance of base case walls. The alternatives were established for the exterior thermal mass for the basement and above ground walls. Similarly, the alternatives for the internal wall mass were established by reversing the position of the concrete walls for the basement and brick walls for the above ground floors at the input file of the base model to be from inside with respect to the insulation of the exterior wall. The simulation results are shown in figure 5.3.

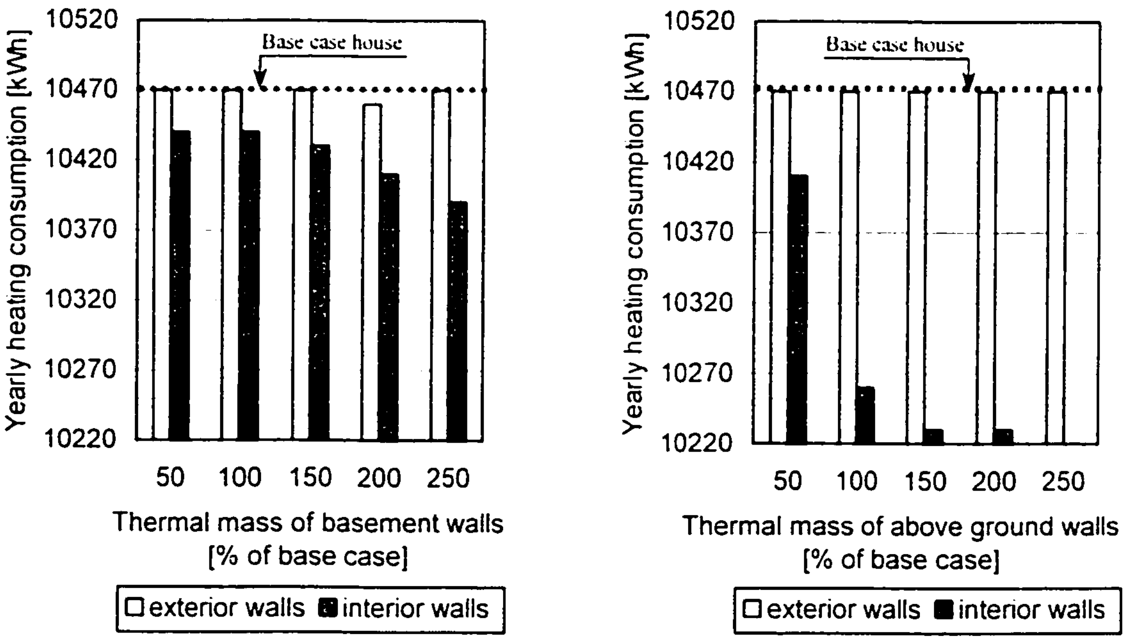


Figure 5.3. Yearly heating consumption vs. exterior and interior thermal mass of walls

Results revealed that the exterior mass walls and the interior mass walls do not have a measured effect on space heating loads during the winter. The small variation of interior temperature between day and night due to the control profile used in the house (along with the small solar gains through the windows) has limited the heat storage effect in the interior mass. However, the interior mass can be used to reduce the interior temperature fluctuations, when a control profile with a large variation for interior temperature between the day and night is used.

Variations of the solar absorptivity for interior and exterior walls

The solar absorptivity coefficient of a surface indicates the amount of direct solar radiation flux, absorbed by that surface. The solar absorptivity coefficient has a scale from 0.0 to 1 presenting the color variance from light to dark colors. The white metallic finish has usually low absorptivity (0.1-0.3), while the black color has approximately 0.9. Five values for the solar absorptivity coefficient were set for the exterior walls of the base case, namely 0.1, 0.3, 0.5, 0.75 (base case) and 0.9.

Similarly, the same values of solar absorptivity coefficient were set for the gypsum board internal walls to examine the impact of color or the solar absorptivity of interior walls on the energy consumption. The combination between the design alternatives of both external and internal walls was established as well by changing the solar absorptivity coefficient for the concrete and brick external walls; and the internal gypsum board walls. Figure 5.4 illustrates the impact of solar absorptivity coefficient on the heating consumption of the base case.

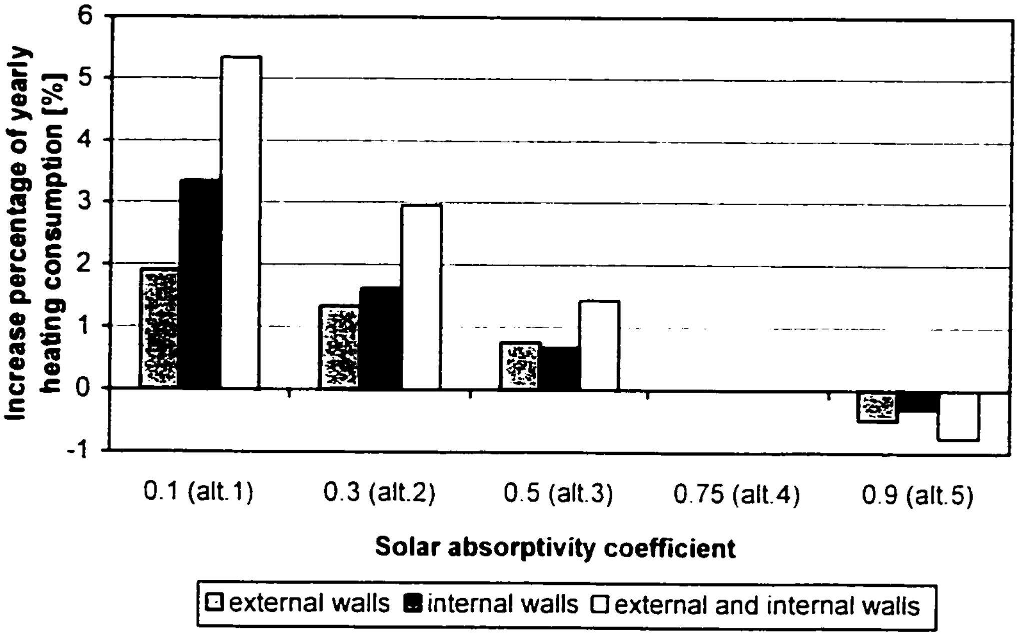


Figure 5.4. Impact of solar absorptivity coefficient on the heating consumption

As shown at the previous figure, there was an increase of the yearly heating consumption of about 1.9%, 3.34% and 5.35% whenever very light reflective colors were applied (alt.1) on the surfaces of exterior walls, interior walls and the combination of interior and exterior walls, respectively. A reduction of 0.3%, 0.5% and 0.8% (alt.5) was noticed whenever darker colors were applied. This indicates that absorptive finishes of building surfaces are preferable for the energy-efficient design.

Installation of the movable insulation on windows

Heat is transferred through glazed opening by two methods: (i) the radiation, convection and conduction through the glazing and window frame from the interior surfaces of windows to outside; and (ii) the infiltration of cold air through the cracks around the window frame.

The window type used in the base case is a well-sealed double glazed unit: therefore the infiltration effect can be neglected. The movable insulation is proposed to improve the thermal properties of windows and to reduce the heat loss due to radiation, convection and conduction. Thermal resistance for movable insulation was assumed to be: 0.0 (base case); 3.5 (R20); 5.3 (R30); 7 (R40); and 8.8 (R50) $m^2 \cdot {}^\circ C/W$. The movable insulation parameter was added to the input file of the base case and the prescribed values were used to establish new computer models.

The schedule of the movable insulation was assumed to be for 24 hours, which means that the movable insulation was installed at the interior side of windows during the day and night for the winter season. This assumption was proposed as the occupants behavior is unknown for the movable insulation usage and in addition, to examine the maximum impact of movable insulation at the heating consumption. Table 5.5 presents the impact of installation of the movable insulations having different thermal resistances.

Table 5.5. Thermal resistance of movable insulation vs. heating consumption

Design alternatives	Thermal resistance [$m^2 \cdot {}^\circ C/W$]	Heating consumption [kWh]	Reduction of heating consumption [%]
Alternative 1 (base case)	0.0	10 470	0
Alternative 2	3.5 (R20)	10 330	1.3
Alternative 3	5.3 (R30)	10 110	3.4
Alternative 4	7.0 (R40)	9 994	4.6
Alternative 5	8.8 (R50)	9 918	5.3

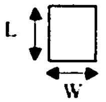
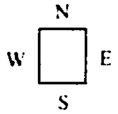
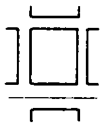
Results from table 5.5 showed that the movable insulation has a small effect on the heating consumption of the base case. For instance, the utilization of movable insulation with thermal resistance of 3.5 $m^2 \cdot {}^{o}C/W$, which is considered as the most applicable and cost-effective alternative led to the reduction of about 1.35% of heating consumption. Movable insulation is not recommended for buildings with double-glazed windows having a high thermal resistance, while it may be more effective to be used with single-glazed windows.

5.1.2 Modifications of the architectural design

Architectural design has a considerable impact on the building design starting from the concept and planning phase till the construction phase of the building as all aspects of building design such as layout, building direction, space location and functions, building form and facade design are undertaken by the architects or building designers. The perception of the impact of architectural design on the energy performance is essential for the design of energy-efficient buildings.

In this chapter, four parameters of architectural design, which expected to have a considerable impact on the energy performance of the base case, were evaluated: building form; glazing-to-wall ratio; building orientation; and presence of close or attached buildings. Table 5.6 illustrates the characteristics of previous parameters of the base case.

Table 5.6. Characteristics of the architectural parameters of the base case

Base-case envelope parameters	Characteristics
Building form Building shape aspect ratio (R), Where R = width (W)/ length (L) 	R = 0.8
Glazing-to-wall ratio [%] Northern facade (N) Eastern facade (E) Southern facade (S) Western facade (W) 	 11.38 1 2 28.75
Building orientation	Northern-southern direction
Presence of close or attached buildings 	Separated building (no attached buildings)

Variations of the building form

The term of building form is used to express the shape of the building envelope, and is expressed using the building shape aspect ratio R = W/L, where W is the building width in the east-west direction, and L is the building length in the north-south direction. The literature search revealed that few studies have been done to optimize the optimum building form. Elongating the rectangular building in the east-west direction was generally recommended to maximize the wall area facing the south to benefit from sunshine in the winter.

In this study five alternatives with different values of R were proposed, for the same floor area to investigate the impact of the building form on the energy performance of the base case. Sketches of the proposed design alternatives for the base case form are shown in figure 5.5.

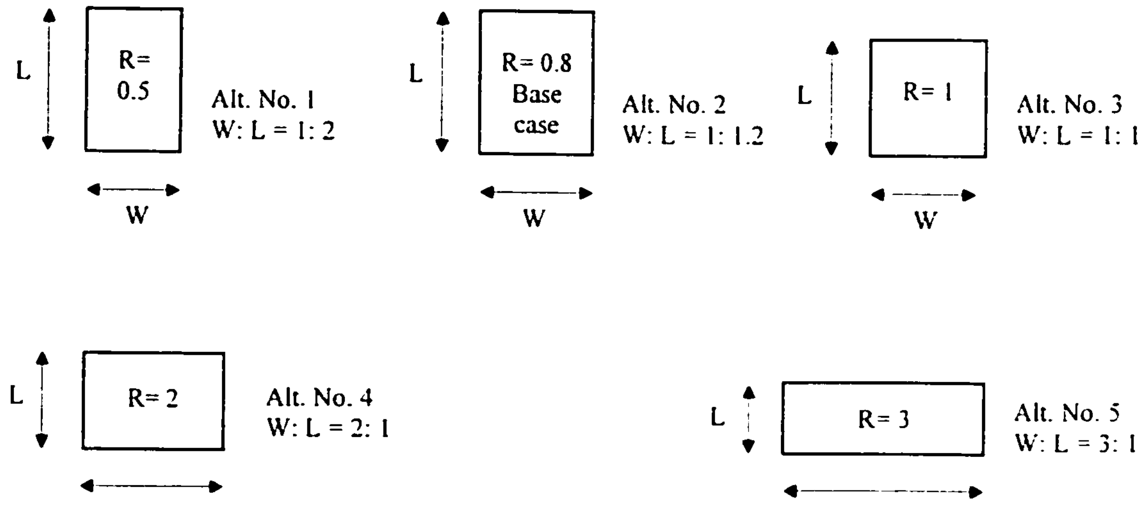
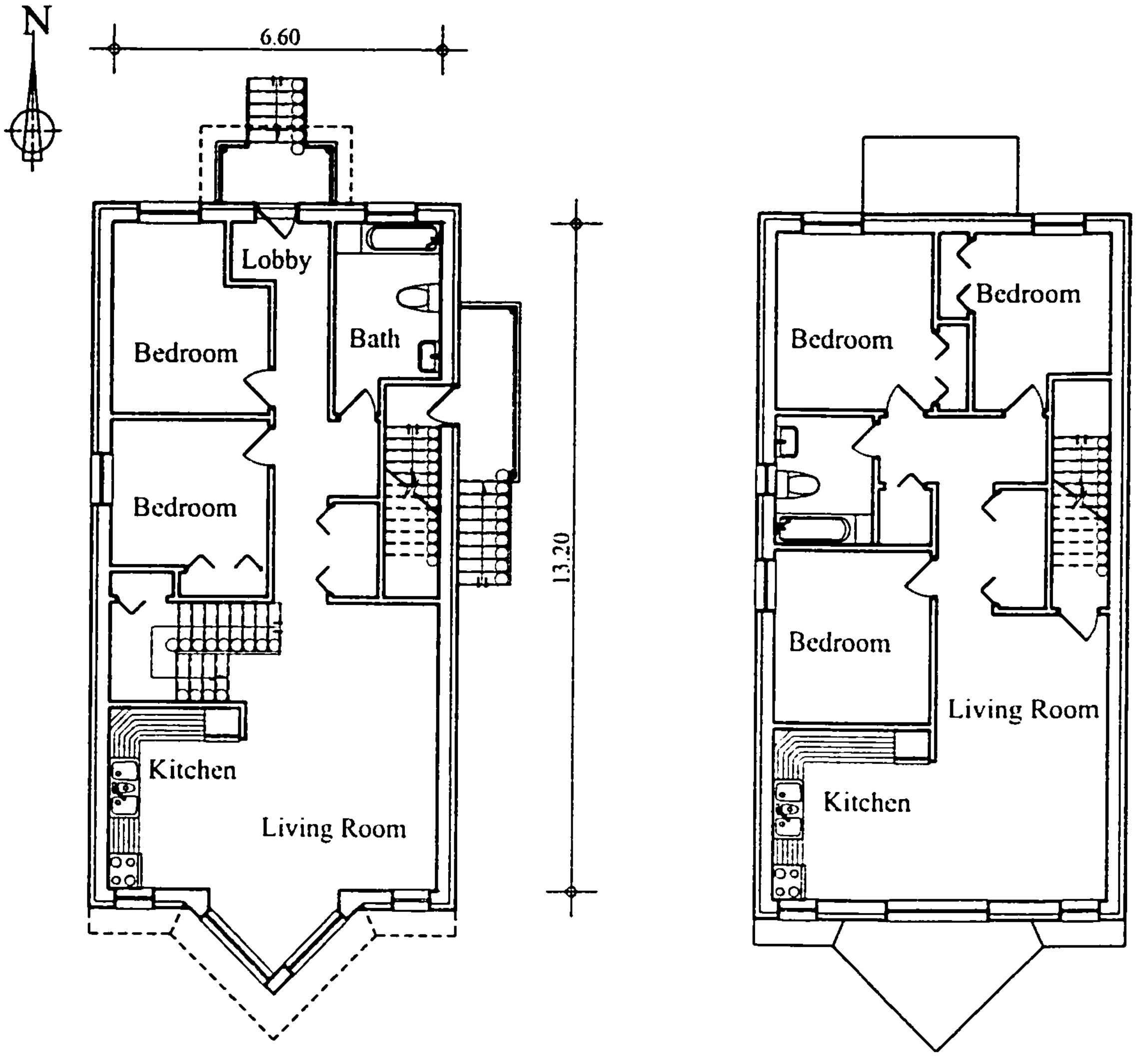


Figure 5.5. Design alternatives for the building form

The minimum ratio value was selected to be 0.5, as shown in figure 5.5 (Alt. No. 1), which assumed to elongate the building in the north-south direction; the simulation results showed an increase of heating consumption of about 3.4% for this alternative. Therefore, for the other design alternatives, the house was elongated in the east-west direction, as displayed in figure 5.5 (R= 1.2 and 3). It was believed that increasing the ratio value over R= 3 will not be applicable, as the architectural design would not fit the new shape. The architectural design for each of such alternatives was modified to fit the new proposed form of the base case. It was assumed that the floor areas, height, volume, and materials characteristics hold the values corresponding to the base case design.

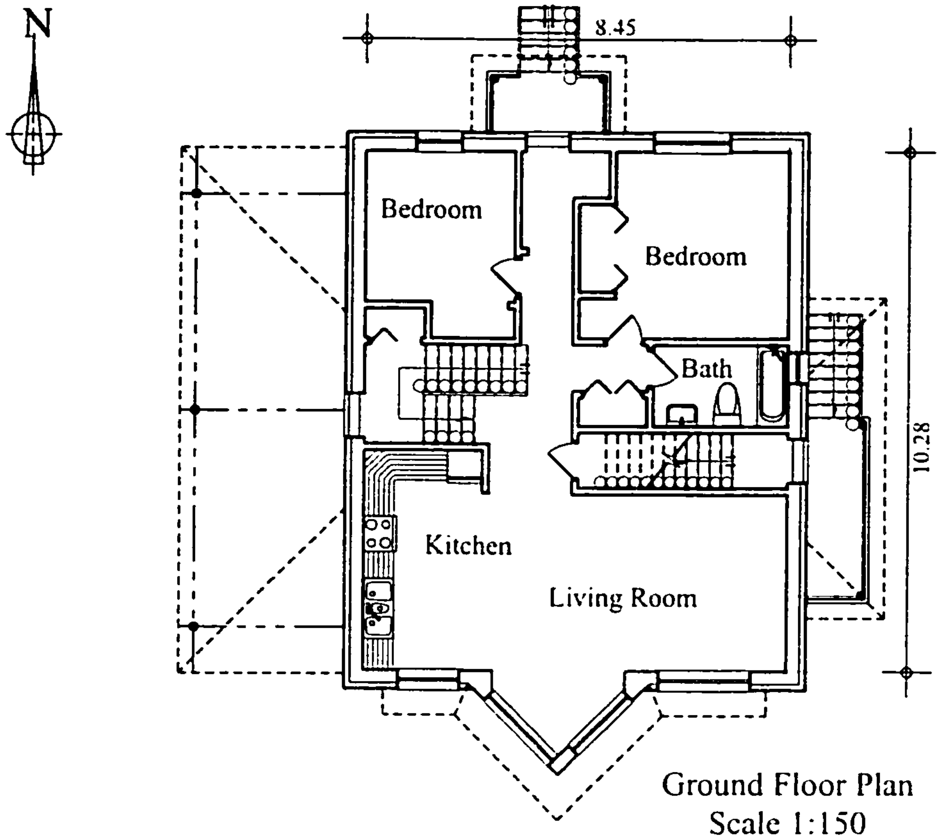
Figures 5.6 to 5.10 illustrate the architectural design, established for the alternatives of the base case form; only ground and first floors are presented as the basement has the similar design as the ground floor.



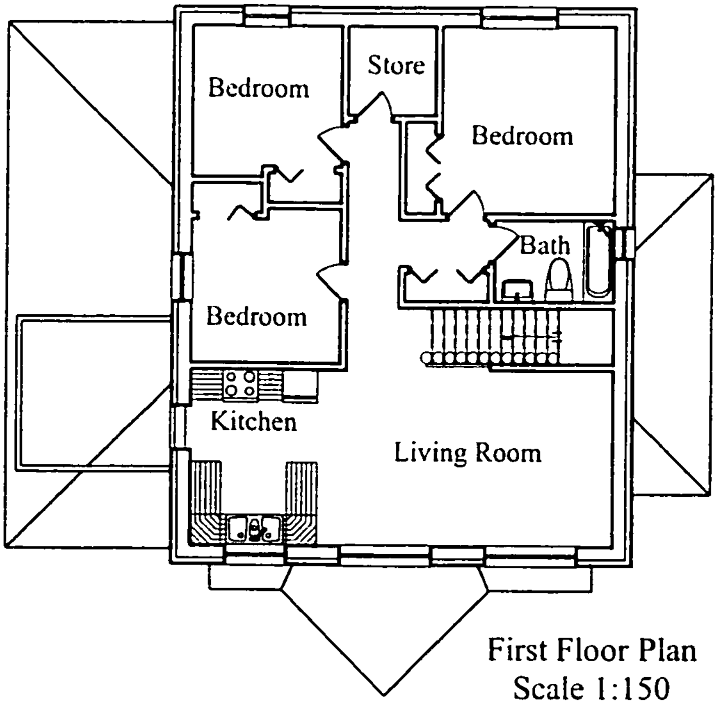
Ground Floor Plan
Scale 1:150

First Floor Plan
Scale 1:150

Figure 5.6. Design alternative no. 1 for width/ length ratio
R = W/L = 0.50

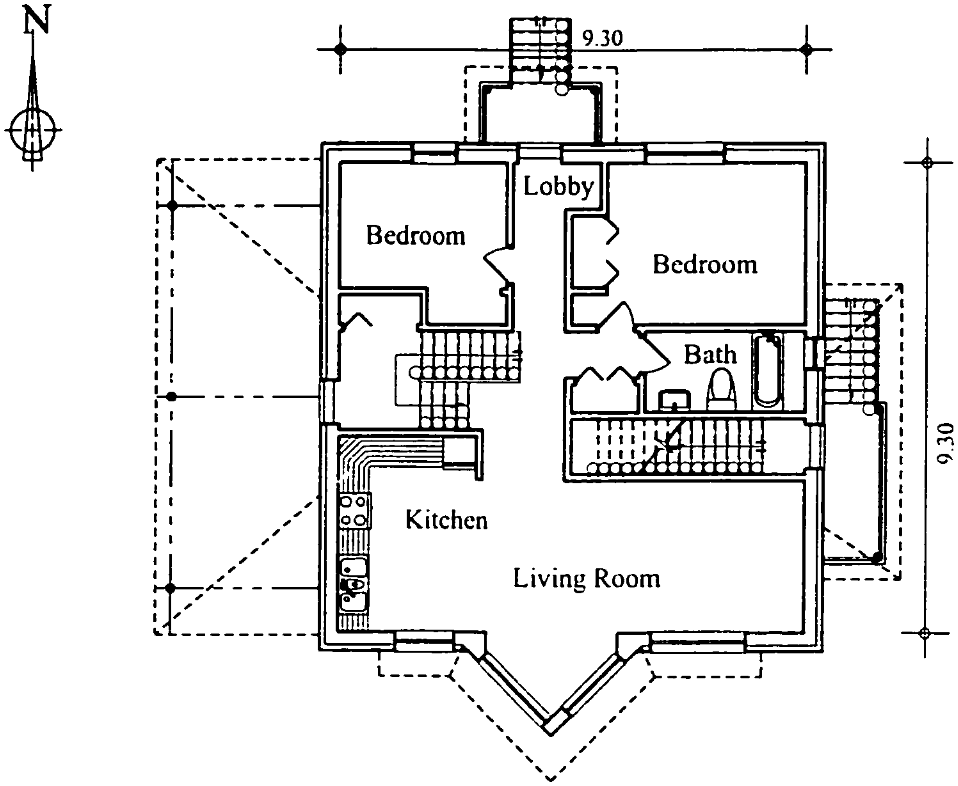


Ground Floor Plan
Scale 1:150

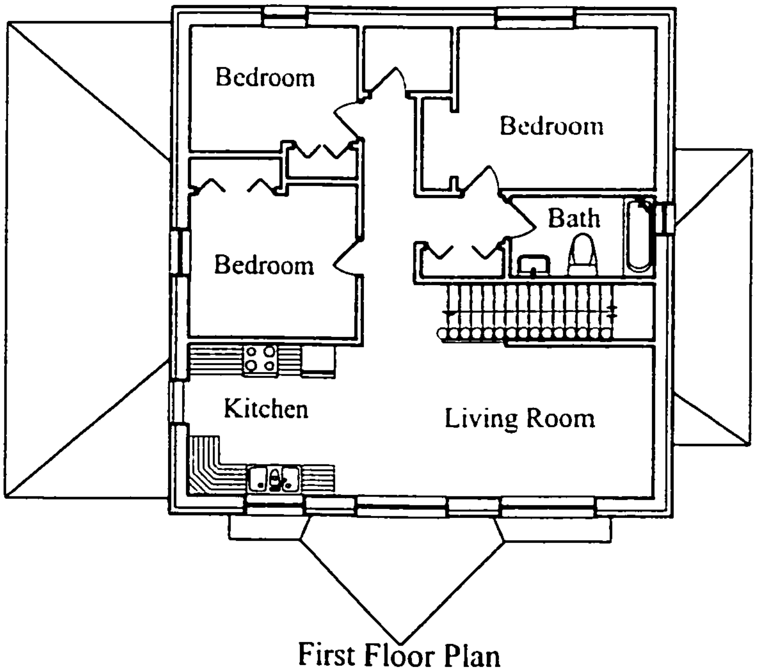


First Floor Plan
Scale 1:150

Figure 5.7. Design alternative no. 2 (base case),
R = W/L = 0.80

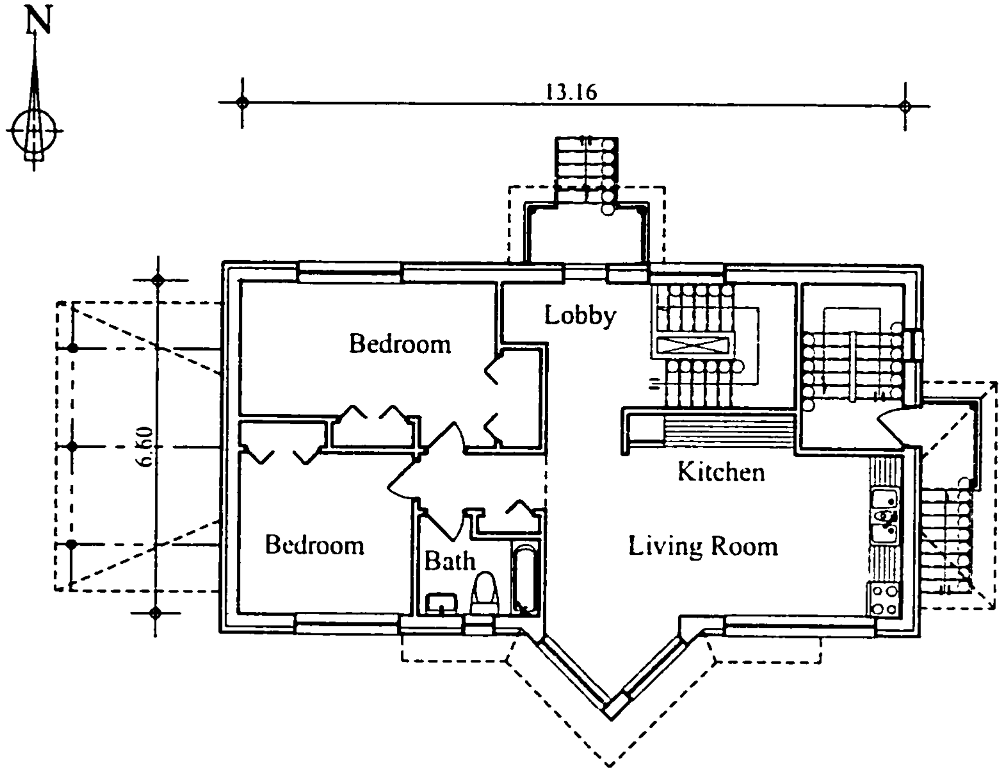


Ground Floor Plan
Scale 1:150

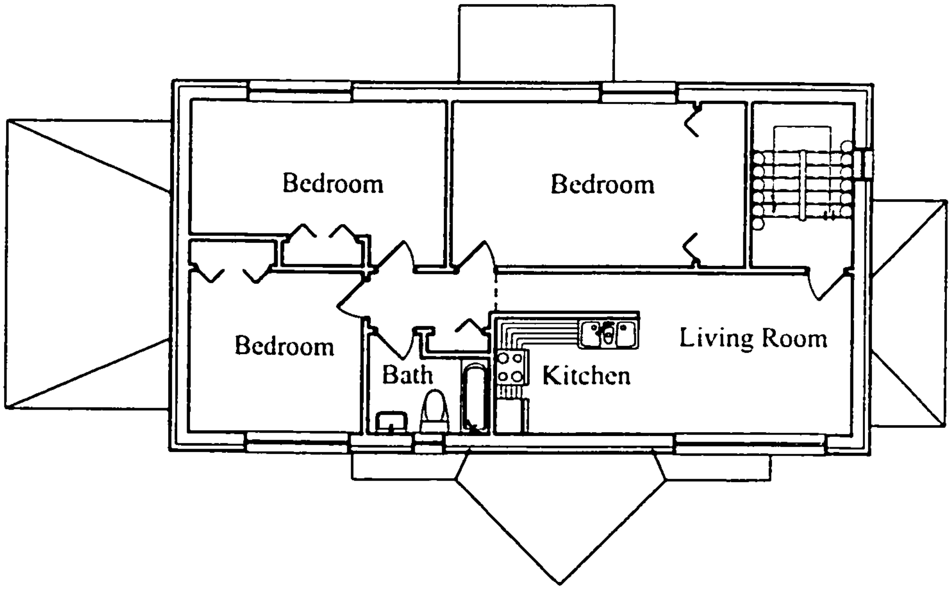


First Floor Plan
Scale 1:150

Figure 5.8. Design alternative no. 3 for width/ length ratio
R = W/L = 1

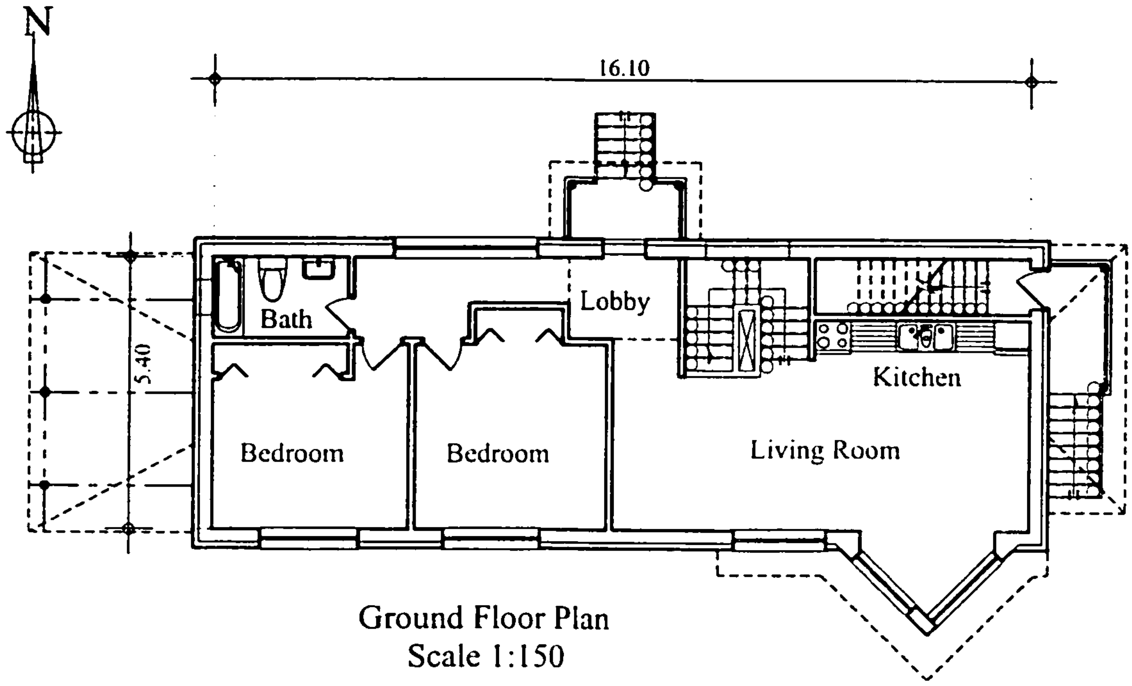


Ground Floor Plan
Scale 1:150

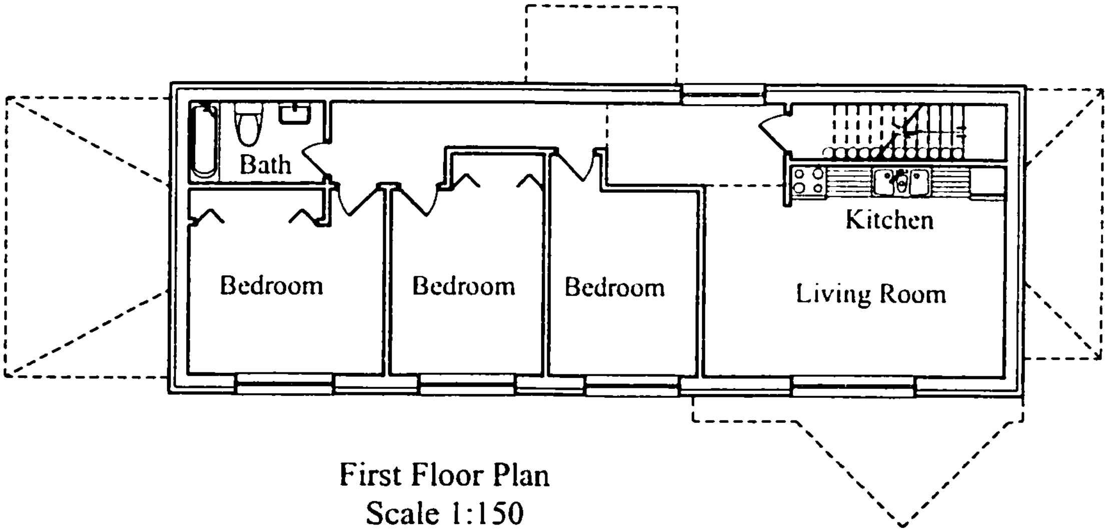


First Floor Plan
Scale 1:150

Figure 5.9. Design alternative no. 4 for width/ length ratio
R = W/L = 2



Ground Floor Plan
Scale 1:150



First Floor Plan
Scale 1:150

Figure 5.10. Design alternative no. 5 for width/ length ratio
R = W/L = 3

Based on the design alternatives, shown in the previous figures, new computer models were established and simulated by using BLAST program. The simulation results are shown in table 5.7.

Table 5.7. Design alternatives with respect to the form of the base case

Design alternatives	Ratio value (R= W/L)	Heating consumption [kWh]	Reduction of heating consumption [%]
Alternative 1 (minimum)	0.5	10 830	- 3.4
Alternative 2 (base case)	0.8	10 470	0.0
Alternative 3	1.0	10 310	1.5
Alternative 4	2.0	10 030	4
Alternative 5 (maximum)	3.0	9 849	6

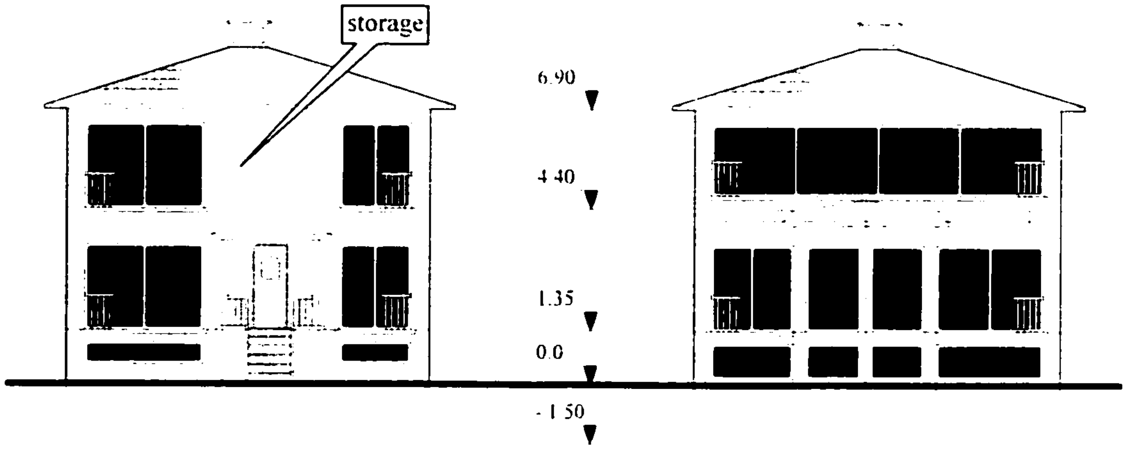
Results form table 5.7 indicated that there was a moderate impact of the building form at the heating consumption of the base case. The use of maximum value of ratio aspect, R = 3 (Alternative 5) led to the reduction of about 6% of the heating consumption with respect to the base case. This impact may be more effective when applied to conventional houses. However, elongating the building in the east-west direction and increasing the area of southern walls are recommended for the energy-efficient design of buildings unless other restricting factors such as layout dimensions and related-regulation limit the utilization of this concept.

Variations of the glazing-to-wall ratio

The glazing-to-wall ratio expresses the percentage ratio of glazing area of building facades to the gross area of such facades, including both fenestration and opaque areas. The glazing area refers to the glazing component of windows and is often surrounded by a sash, connected to a frame, which is fixed to the building wall; the entire assembly of the sash, glazing and frame is known by the term of window. Increasing the glazing area on the south facing facades and minimizing it at the other facades is one of the major energy-efficient concepts used by designers. This approach helps to reduce the heating loads by increasing the solar heat gain. Five alternatives for the glazing-to-wall ratio for each facade of the base case were proposed.

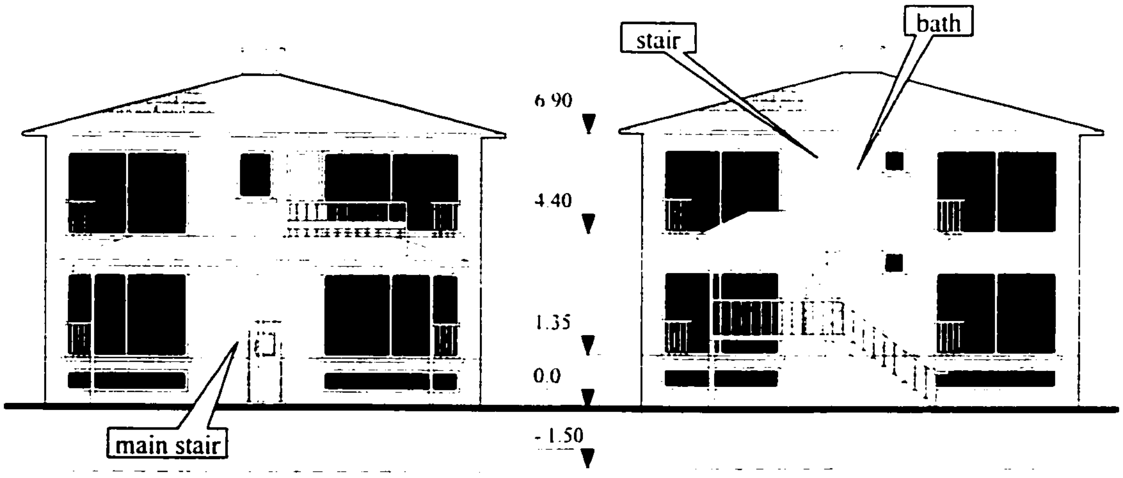
The glazing-to-wall ratio of the base case is 11.38%; 1%; 2% and 28.75% for the northern, eastern, western and southern facades, respectively. For the northern facade, the minimum value of the glazing-to-wall ratio was selected to be 0% assuming that the entire facade is opaque. The maximum value was set to be 39%; this value was selected based on the architectural and structural design and the function of spaces of the base case. For instance, the windows lintel of the design alternatives was set at the similar height of exterior and interior doors, which is 2.15 m from the floor for each story of the building and that to maintain the aesthetics and regime of the facades, creating a balanced architectural statement, and to keep the consistency of the house structure. Due to the windows lintel, exterior wall thickness and the entrance area, the maximum applicable value for the glazing-to-wall ratio of the northern facade was 39%. Similarly, the design alternatives for the other facades were proposed.

The minimum value for the southern facade was set at 0% while the maximum value was 60%. The minimum value for the eastern and western facades were set at 1% and 2% respectively, while the maximum value was 40%. The limitation of increasing the glazing areas at such facades was due to the presence of the exterior stair and bathrooms for the eastern facade and the locating of the main stair for the western facade. Figure 5.11 illustrates the maximum proposed glazing area of each facade.



Northern facade

Southern facade



Western facade

Eastern facade

Figure 5.11. Design alternatives for the maximum glazing area of the base case facades

Three intermediate values of 11.38% (base case); 20% and 30% were proposed for the glazing-to-wall ratio of the northern facade, thus creating five alternatives for this facade. Similarly, three intermediate values of 15%; 28.75% (base case) and 45% were proposed for the southern facade, while they were 10%, 20% and 30% for the eastern and western facades, respectively. The simulation results for the facades are presented in figure 5.12.

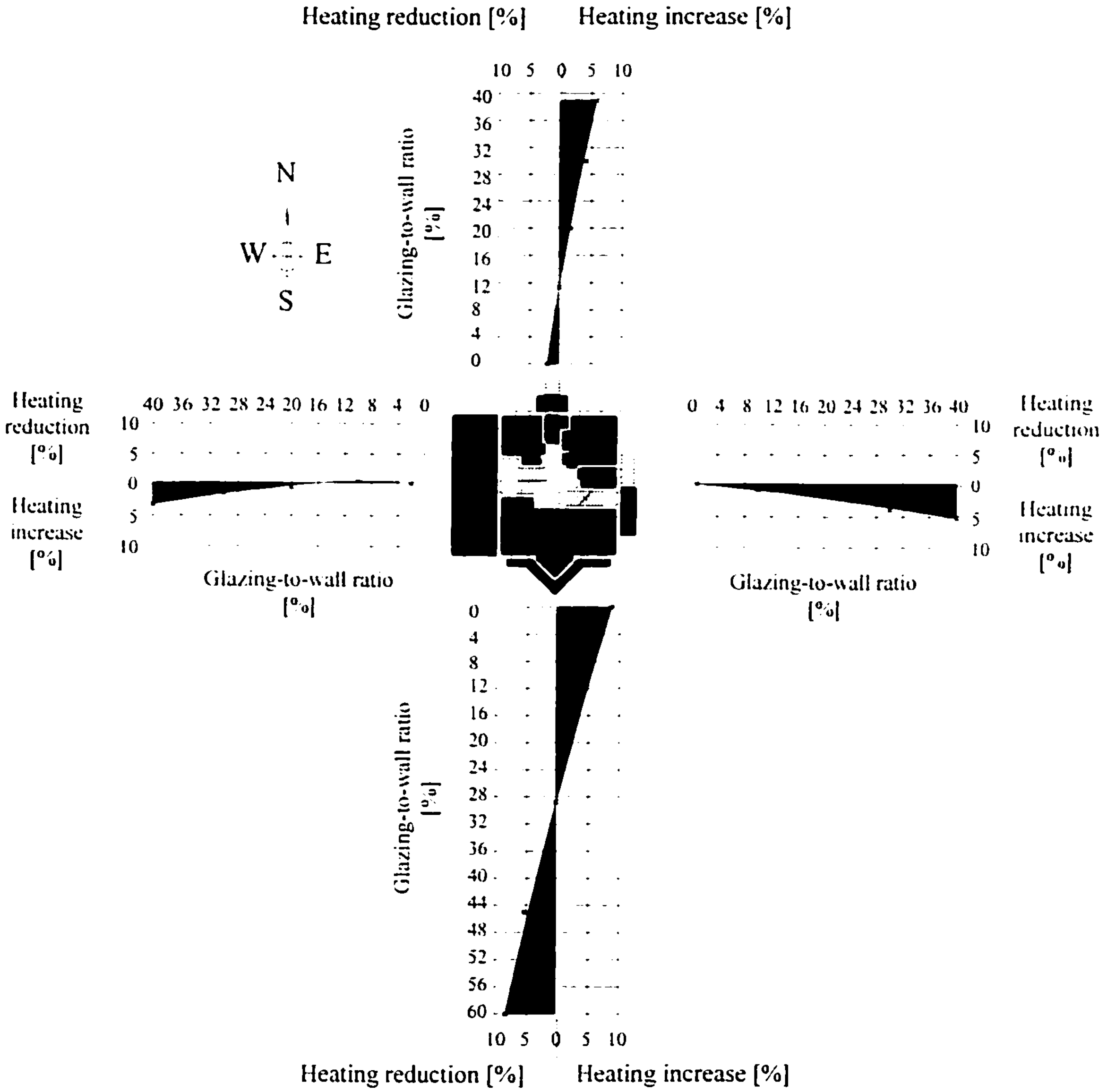


Figure 5.12. Impact of glazing-to-wall ratio on the heating consumption of the base case

Results indicated that the increase of south facing glazing reduced the energy consumption, while the increase of glazing for other facades led to the increase of energy consumption. For instance, increasing the glazing-to-wall ratio from 28.75% to 60% on the southern facade led to the reduction of 7.7% of yearly heating consumption, while increasing the glazing area at the northern facade from 11.38% to 39% led to increase of heating consumption by 5.7%. The increase the glazing area from 1% to 40% and from 2% to 40% for the eastern and western facades, respectively, resulted in heating increase of about 5.2% and 3.2%, respectively, which indicates that the west facade is less sensitive to the increase. Furthermore, the combinations between the design alternatives for the glazing-to-wall ratio were proposed as follows:

1- Alternative no.1: glazing-to-wall ratio of northern facade (N)= 39%; eastern facade (E) = 1% (base case); western facade (W) = 2% (base case) and southern facade (S) = 0%; and

2- Alternative no.2: a combination of the glazing-to-wall ratio of northern facade (N)= 0%; eastern facade (E) = 1% (base case); western facade (W) = 2% (base case) and southern facade (S) = 60%.

The simulation results for these alternatives are presented at table 5.8.

Table 5.8. Total glazing-to-wall ratio alternatives vs. heating consumption

Design alternatives for glazing-to-wall ratio [%]	Heating consumption [kWh]	Reduction of heating consumption [%]
Base case: (N=11.38, E=1, W=2, S=28.75)	10 470	0.0
Alternative 1: (N=39, E=1, W=2, S=0)	12 990	-24
Alternative 2: (N=0, E=1, W=2, S=60)	9 455	9.7

The results of the combination of maximum glazing-to-wall ratio of northern facade and minimum value for the same parameter for the southern facades (Alternative 1, Table 5.8) indicated an increase of 24% of yearly heating consumption. This increase of 24% exceeds the sum of 5.7% increase for the maximum glazing-to-wall ratio of northern facade, and 8.5% for minimum glazing-to-wall ratio of southern facade, when these alternatives were applied individually. Therefore, it is essential to consider the total impact of glazing-to-wall ratio for the four facades of a building on the energy consumption. For instance, increasing the glazing areas of the northern facade or eastern and western facades should be offset by increasing the glazing area of southern facade, otherwise a significant increase of heating would occur.

Variations of the house orientation

The house orientation is a term used to express the direction of the house and its location on the site. Based on rules of thumb, the houses were recommended to be shaped along the east-west axis to increase the area of exterior walls area facing the south, in order to increase the solar contribution to heating. Due to the site restrictions, the Ray-Vision house was elongated in the north-south axis, as described in chapter 3. The impact of the base case orientation was examined in this chapter by modifying the rotation angle. As the house has a large glazing area at the southern facade, the design alternatives for the rotation angles were assumed to be from 90° to –90°, as shown in figure 5.13 because increasing the rotation angles above the 90° to –90° would led definitely to increase of the base case energy consumption, as the southern facade would face the north-east or north-west directions in this case.

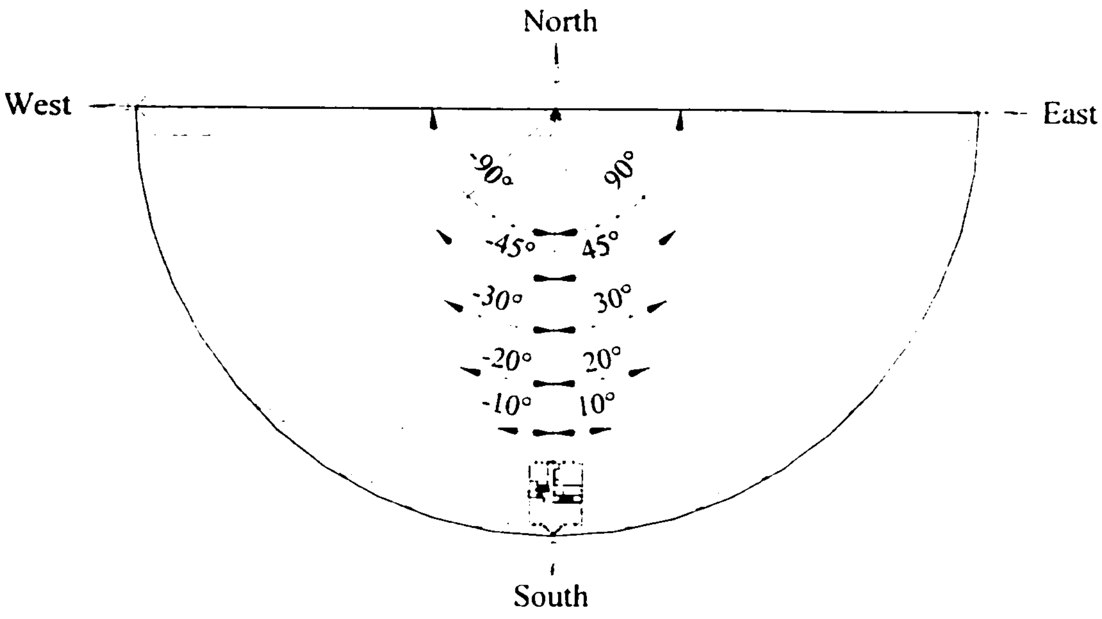


Figure 5.13. Design alternatives for the house orientation

The simulation was performed for several rotation angles and the results are presented in figure 5.14.

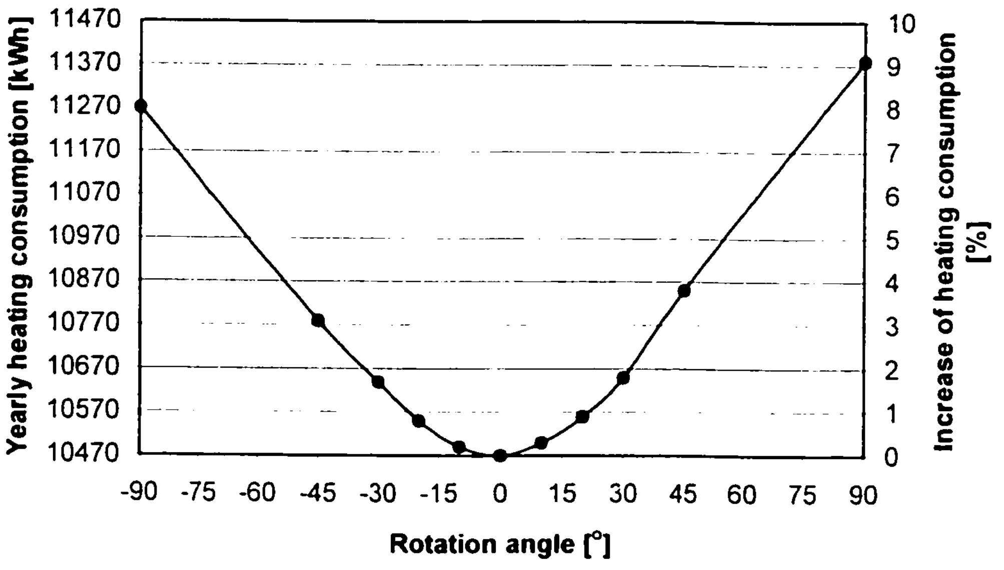


Figure 5.14. Yearly heating consumption versus rotation angle

The rotation angle for the base case is 0°, which indicates an orientation in the north-south direction. However, the heating increase of the alternatives of rotation angles between -30° and 30° was insignificant, e.g. the heating increase was about 1.7%, when the house was directed to -30° or 30°. This indicates that buildings can be located in the direction between -30° and 30° without affecting the energy performance of these buildings. On the other hand, a considerable increase of heating was remarked when the base case was rotated with an angle above -30° and 30°. For instance, the rotation angle of 90° led to increase of about 8.7% of heating.

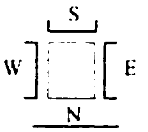
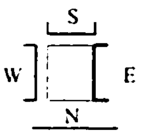
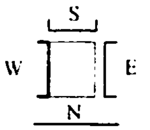
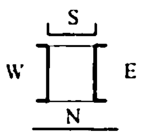
Presence of close or attached buildings

The Ray-Vision house is located on a main street facing the northern facade of the house and an open space at the south. Two neighborhood buildings are adjacent: one of them is facing the eastern facade while the other is facing the western facade. Both buildings have a distance of about 6 m from the house and cause shading at the eastern and western facades of the house. The distance between the base case and the adjacent buildings was modified to optimize the shading effect at the energy performance of the base case. However the simulation results showed insignificant impact of shading due to adjacent buildings at the base case. For instance, the heating increase of about 0.5% whenever the buildings were close by half distance from the base case. It is expected that shading has a considerable impact at the energy consumption for cooling at the summer, which is out of scope of this research. The adjacent buildings were assumed to be attached on the eastern facade of the base case as the first alternative, and at the western facade as a second alternative.

The third alternative was proposed to have attached buildings at both eastern and western facades of the base case. For instance, for the alternative with the western attached building, the western exterior wall of the base case was removed from the input file of the base case; thus the heat transfer through this wall would not be calculated by BLAST. This process is based on the assumption that the attached building is a heated space and no heat transfer occurs between the base case wall and the attached building.

In addition, the attached building affects the air infiltration rate of the house. The infiltration rate for the western attached building alternative was reduced, assuming that no infiltration occurs through the west wall. Similarly, the other attached building alternatives were proposed and their computer models were developed. The simulation was performed by BLAST program and the results are presented in table 5.9.

Table 5.9. Attached buildings alternatives vs. heating consumption

Design alternatives		Heating consumption [kWh]	Reduction of heating consumption [%]
Base case (no attached buildings)		10 470	0.0
Alternative 1 (eastern attached buildings)		8 874	15.2
Alternative 2 (western attached buildings)		6 839	34.7
Alternative 3 (eastern and western attached buildings)		5 308	49.3

Results revealed a significant impact of attached buildings on the energy consumption of the base case; e.g. the heating reduction due to the western attached building is 34.7%. On the other hand, the attached building from the west (Alternative 2) affected the heating consumption more than the attached building from the east (Alternative 1), because the infiltration rate is greater on the west wall due to the prevailing wind direction in Montreal.

5.1.3 Modifications of the building operating conditions

The pattern of usage and life style of the house occupants have a considerable influence on the energy performance of the house. From the analysis of house operating conditions (Chapter 4), the occupants behavior affected the thermostat setpoint temperature, through adjusting it at 21°C during the day and 15°C at the night for the ground and second floors, while it was set continuously at 10°C for the basement during the day and night. Modification of the thermostat setpoint for the heating is examined in this section.

Variations of the thermostat setpoint for heating

The thermostat setpoint temperature was modified in the final calibrated computer model and is set to be 21°C by day, expressed in the term of (1 at 20°C- 0 at 22°C) and 18°C at night, expressed in term of (1 at 17°C- 0 at 19°C). The minimum value proposed for this parameter was set at 17°C during the day and 14°C at night. These values were selected to be 4°C less than the setpoint temperature of the base case. The other alternatives use values, which increase by 1°C at a time above the minimum alternative for the day and night, respectively, as shown in table 5.10.

Table 5.10 presents the different values of design alternatives for the thermostat setpoint temperature and their impact on the heating consumption.

Table 5.10. Thermostat setpoint temperature vs. heating consumption

Design alternatives	Thermostat setpoint temperature [°C]	Heating consumption [kWh]	Reduction of heating consumption [%]
Alternative 1	17°C at day- 14°C at night	6 832	34.8
Alternative 2	18°C at day- 15°C at night	7 685	26.6
Alternative 3	19°C at day- 16°C at night	8 578	18.1
Alternative 4	20°C at day- 17°C at night	9 507	9.2
Alternative 5 (base case)	21°C at day- 18°C at night	10 470	0.0
Alternative 6	22°C at day- 19°C at night	11 460	-9.5
Alternative 7	23°C at day- 20°C at night	12 470	-19.1
Alternative 8	24°C at day- 21°C at night	13 510	-29.05

The following figure 5.15 illustrates the correlation between thermostat setpoint temperature and the heating consumption of the base case house.

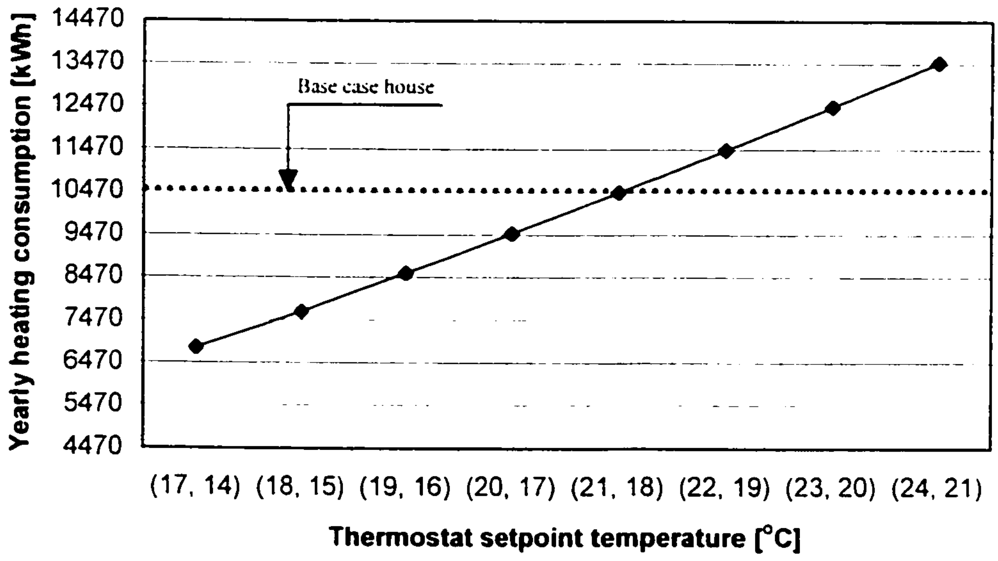


Figure 5.15. Correlation between thermostat setpoint temperature and heating

Results from figure 5.15 revealed a significant impact of the house operating conditions on the energy performance of the base case. For instance, by reducing the thermostat setpoint by 1°C by the day and night (Alternative 4, Table 5.10), the reduction of heating of 960 kWh or 9.2% can be achieved. The average of 950 kWh for heating consumption reduction was derived from the simulation results (Table 5.10), when the thermostat setpoint temperature was decreased by 1°C than the base case for the day and night.

5.2 Non-parametric analysis approach

The parametric approach was used to optimize the impact of the material characteristics, architectural design and the operating conditions on the thermal performance of the base case. Although this approach is essential for building design, there is still a potential for improving the energy performance of building by using the non-parametric approach. The non-parametric approach is a step forward allowing the building designers to introduce new creative concepts, which eliminate the restrictions of the parametric approach. Two innovative designs of the base case house are proposed based on the following criteria:

1- The design alternatives hold the similar characteristics of the base case with respect to the materials properties, air tightness, floor area, height, glazing-to-wall ratio, and number of stories.

2- The main difference between the proposed alternatives and the base case is the use of an attached greenhouse, the change of building form, and spaces location (e.g. the location of the bedrooms and reception was modified).

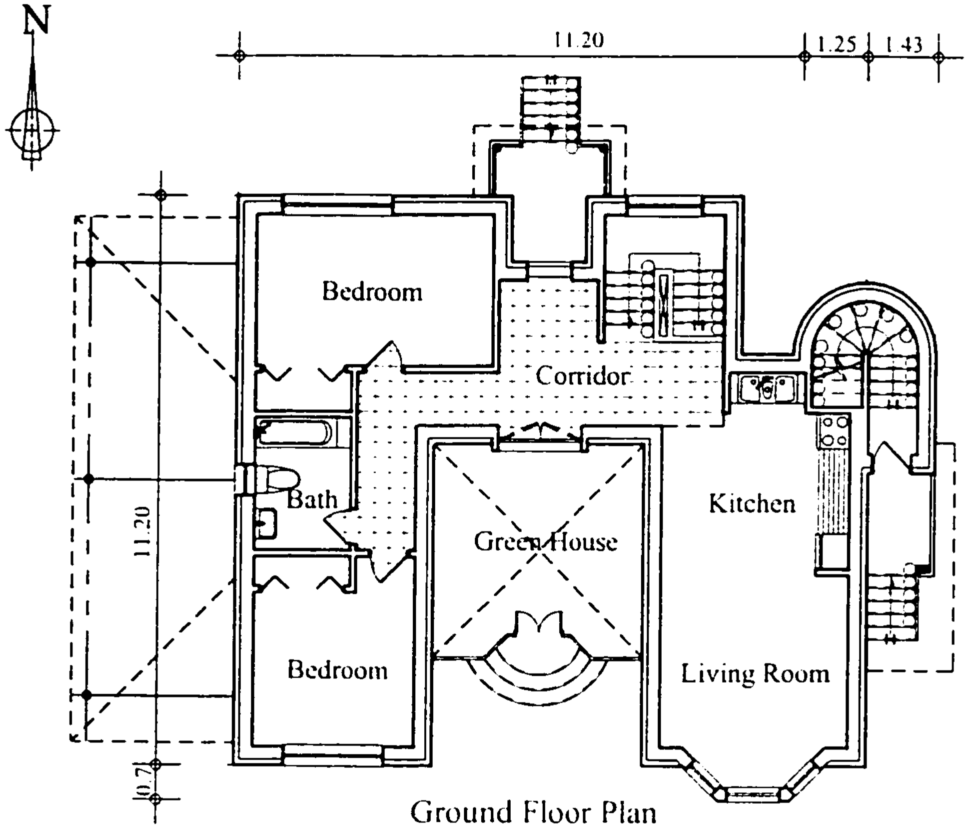
3- The restrictions of the layout are waived, assuming that the house is located at an open space site.

Design alternative no. 1

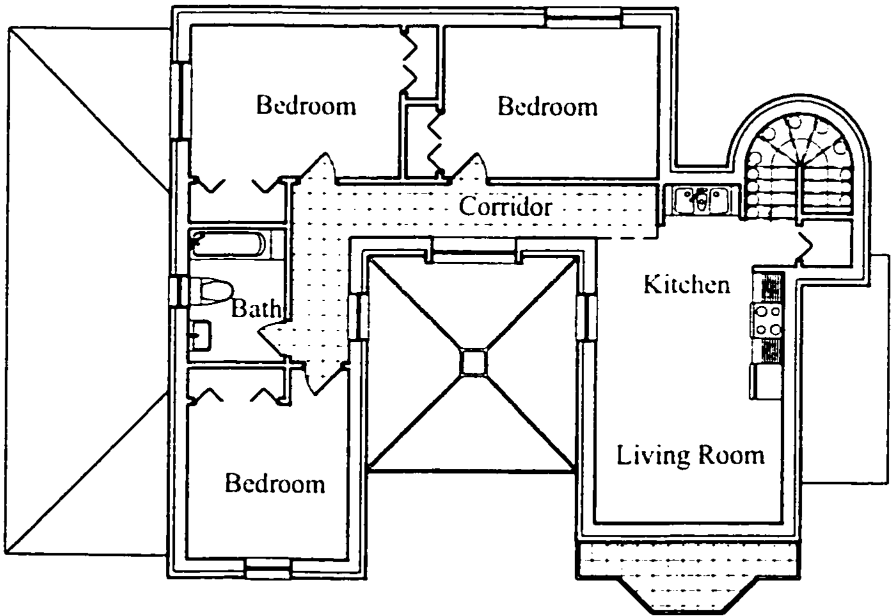
The concept of this alternative is based on the use of a compacted form for the house with aspect ratio R (width/ length) almost equals to 1. The square form is used to allow the greenhouse to be placed within the house. Since most of the greenhouses are attached from one side or semi-attached to the southern walls of houses, the greenhouse of the proposed design alternative is located within the house and facing the south. The greenhouse is connected with other spaces such as bedrooms and living room with three sides (walls) of the greenhouse. This approach reduces the glazing walls of the greenhouse, which are exposed to the sun to reduce the interior overheating.

The design criterion used for this alternative from the point of view of energy-efficient design included: (i) locating the living room to the south direction, while the bedrooms were located to the south and east directions; (ii) locating the staircases and entrance at the north to be used as a buffer zones, which reduce the effect of the northern wind to the other house zones; and (iii) adding a greenhouse within the house with a direct link to most of the house rooms. A concrete wall with a thickness of 0.3 m and without insulation was installed for the walls between the house and greenhouse.

Figure 5.16 presents the ground and second floors for the alternative design no. 1, the basement design was assumed to be similar to the ground floor.



Ground Floor Plan
Scale 1:150



Second Floor Plan
Scale 1:150

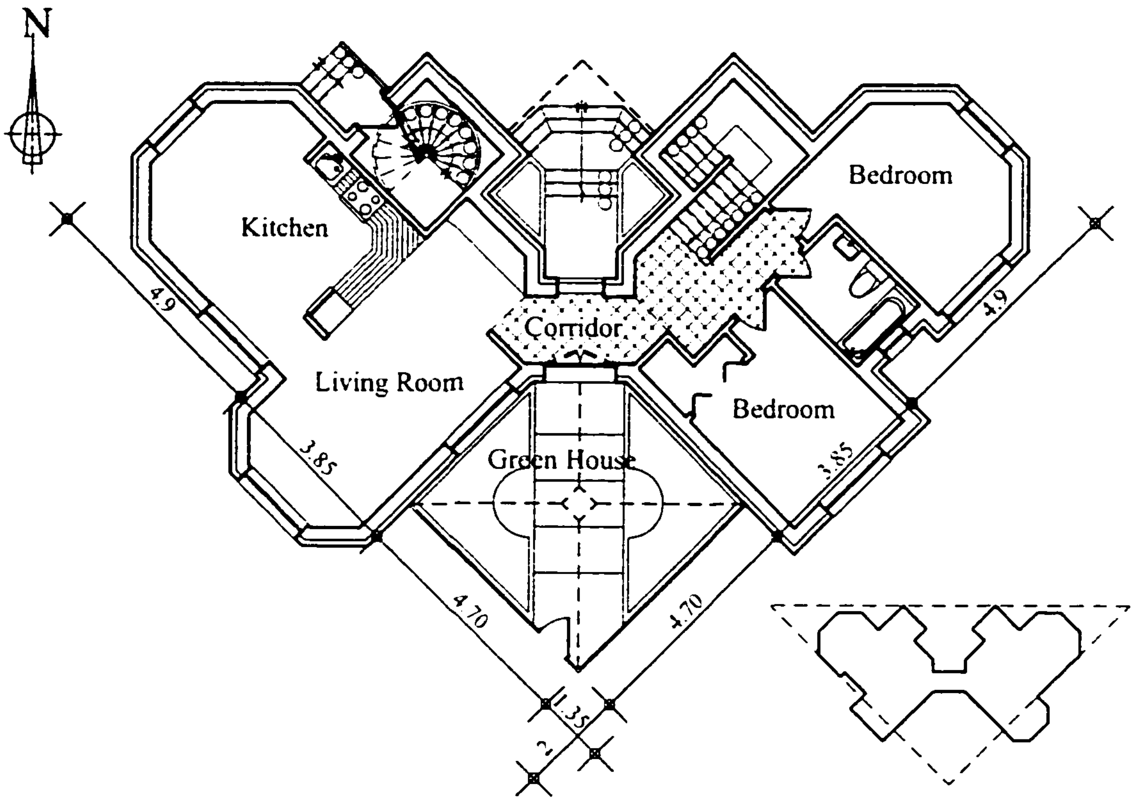
Figure 5.17. The non-parametric design alternative no. 1

The simulation results revealed that the yearly energy consumption for heating was 8820 kWh or reduction of about 15.80% with respect to the base case. Although the heating reduction is significant for this proposed design, it is expected to have further reduction, if this concept would be implemented in the conventional houses.

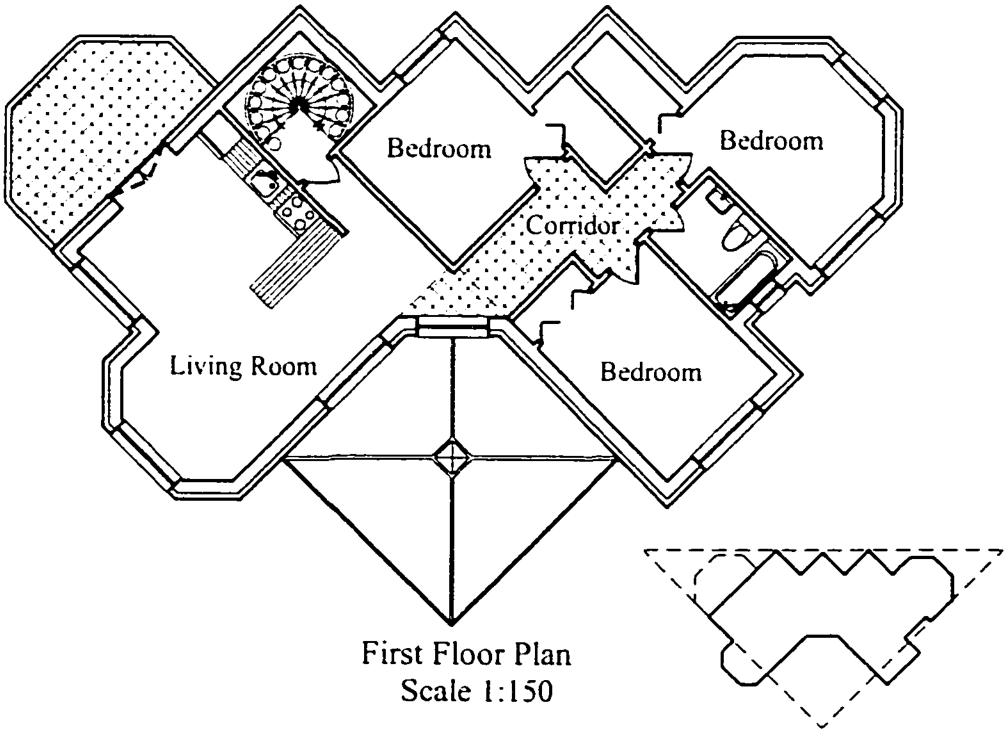
Design alternative no. 2

Another concept was proposed for the base case house. The design elements used for this alternative included: (i) shaping the building form in a triangle figure to increase the exterior walls of the house exposed to the sun from the south-east and south-west directions; (ii) locating the staircases and a protected entrance at north, acting as a buffer zone; (iii) locating most of the house spaces such as bedrooms and living room so that their exterior walls were facing the south-east and south-west, in order to increase the solar radiation within the house and to improve the thermal comfort in the winter; shading devices were assumed to be installed for the summer; and (iv) attaching the greenhouse to the house from the south with a concrete wall of 0.3 m thickness, acting as a mass wall to store the heat gain at the day.

Figure 5.17 presents the ground and second floors for the alternative design no. 2, the basement design was assumed to be similar to the ground floor.



Ground Floor Plan
Scale 1:150



First Floor Plan
Scale 1:150

Figure 5.16. The non-parametric design alternative no. 2

The simulation results revealed that the yearly energy consumption for heating was 9757 kWh or reduction of about 7% with respect to the base case. The difference between the results of alternative no. 1 and alternative no. 2 is due to the more compact design used for alternative no. 1, whereas the greenhouse was located at the middle of the house. Moreover, the triangle form of alternative no. 2 tolerated the living room and bedrooms to have direct connection with the south and north direction at the same time: therefore most of the heat gain from the south was offset by the heat loss to the north.

Although the greenhouse effect was examined for the heating load for the winter, which is the scope of this study, the main concern was regarding the overheating in the summer. Several techniques can be used to reduce the interior overheating, including covering the glazing walls of the greenhouse with a movable insulation and opening the glazing roof to allow for air movement.

5.3 Summary of results for the best design alternatives

From the previous discussion, there is still a potential for improving the energy performance of building through variation of parameters and exploration of different approaches, as described in this chapter. Results show that most of selected design alternatives have a considerable impact on the energy consumption of the base case. Five design parameters, which have the significant impact on the energy performance of the base case are investigated and presented in table 5.11.

Table. 5.11. Design alternatives having the optimum impact on the energy performance

Parameters	Yearly heating consumption [kWh]
Thermal resistance of basement, above ground walls and roof [$m^2.^oC/W$]:	
2.2, 3.4 and 5.3	14 610
8.8, 10.57, 17.61	7 775
Thermal resistance for windows [$m^2.^oC/W$]:	
0.36	12 140
0.88	9 366
Glazing-to-wall percentage for north (N); east (E); west (W) and south (S) facades [%]:	
N= 39, E= 1.0, W=2.0, S= 0.0	12 990
N= 0.0, E= 1.0, W=2.0, S= 60	9 455
Airtightness [ach]:	
3	15 860
0.6	8 612
Setpoint heating temperature [^oC]:	
24°C at day and 21°C at night	13 510
17°C at day and 14°C at night	6 832

The performance of the design alternatives is evaluated with respect to the life-cycle analysis, including the energy consumption, cost, and environmental impact. The evaluation for the design alternatives, developed in this chapter, is presented in chapter 6.

CHAPTER 6

DECISION SUPPORT SYSTEM BASED ON THE LIFE-CYCLE ANALYSIS OF DESIGN ALTERNATIVES

An extensive study was carried out in chapter 5 to define the design alternatives and assess their related-energy impact, in order to further improve the energy performance of the base case house. In this chapter, the life-cycle analysis approach is utilized to assess the effectiveness of the design alternatives during the lifetime of the house from the point of view of cost, energy use and the environmental impact. The information obtained from the life-cycle analysis for design alternatives was used to establish a decision support system for energy-efficient design of new houses.

6.1 Multi-attribute life-cycle analysis

There are three objective functions used in the life-cycle analysis: (1) the life-cycle energy, which expresses the total energy consumption, including the initial or embodied energy and the operating energy; (2) the life-cycle cost, including the initial or investment cost and the operating costs; and (3) the environmental impacts, evaluated by using the Global Warming Potential (GWP) index, which is calculated in terms of equivalent CO_2 emissions. These emissions are generated during the process of manufacturing and installing the building components, and by utilizing energy for operation, over the life cycle.

6.1.1 Life-cycle analysis of energy

The total energy consumption for the base case house includes the initial or embodied energy of construction materials, and the energy used by the operation of the building over its lifetime.

Embodied energy

The literature search revealed a significant impact of the embodied energy on the total energy consumption of buildings. Two recent resources were mainly used in this study: ATHENA software program (2000) and Alcorn. A. (1998). Other resources were used whenever a lack of information exists, as shown in table 6.1. The embodied energy of the base case was estimated using the information from drawings and specifications. The embodied energy of plumbing, electrical, heating and ventilation systems are not included in this study. The total embodied energy of the base case house was estimated at 707863 MJ (Table 6.1) or 635 kWh/m^2 of floor area. This value reveals that the embodied energy has a considerable impact compared to the annual heating consumption of the house, which is 34 kWh/m^2. The embodied energy of the base case is equal to about 19 years of the energy consumption for heating.

The embodied energy of the design alternatives was evaluated similarly to the base case calculations, whereas the reduction and increase of embodied energy for the design alternatives was due to the modifications of design and materials characteristics of these alternatives. Table 6.1 presents the inventory of the embodied energy for the base case.

Table 6.1. Inventory of embodied energy for the base case

Parameters	Total embodied energy [MJ]	Specific embodied energy [MJ/ unit]	Reference
Site work			
Foundations	18 600	1550 per foundation	[Athena, 2000]
Slab on grade			
Concrete	22 083	208.76/ m^2	[Athena, 2000]
Thermal insulation (0.05 m polystyrene)	18 564	117/ kg	[Alcorn, 1998]
Vapor barrier (polyethylene 6 mm)	529	5/ m^2	[Athena, 2000]
Envelope			
Basement envelope			
Water proof (bitumen)	5 434	45420/ m^3	[Alcorn, 1998]
Reinforced concrete (thick 0.25 m)	46 281	1480/ m^3	[Athena, 2000]
Thermal insulation (0.05 m polystyrene)	20 993	117/ kg	[Alcorn, 1998]
Wood studs 2x4 @ 0.6 m c.c.	3 864	32.3/ m^2	[Athena, 2000]
Thermal insulation (0.9 m cellulose)	2 368	4.4/ kg	[Alcorn, 1998]
Wood studs 1x4 horizontal @ 0.6 m c.c.	2 822	23.59/ m^2	[Athena, 2000]
Vapor barrier (polyethylene 6 mm)	598	5/ m^2	[Athena, 2000]
Gypsum board	6 519	47/ m^2	[Athena, 2000]
Ground and second floors envelope			
Brick veneer (thick 0.1 m)	179 900	881/ m^2	[Athena, 2000]
Building paper	24 708	121/ m^2	[Athena, 2000]
Sheathing	13 130	64.3/ m^2	[Athena, 2000]
Wood studs 2x2 @ 0.6 m c.c.	4 817	23.59/ m^2	[Athena, 2000]
Thermal insulation (0.38 m polystyrene)	35 838	117/ kg	[Alcorn, 1998]
Wood studs 2x6 @ 0.6 m c.c.	7 012	34.34/ m^2	[Athena, 2000]
Thermal insulation (0.14 m cellulose)	6 065	4.4/ kg	[Alcorn, 1998]
Wood studs 1x4 horizontal @ 0.6 m c.c.	4 817	23.59/ m^2	[Athena, 2000]
Vapor barrier (polyethylene 6 mm)	1 021	5/ m^2	[Athena, 2000]
Gypsum board	11 129	47/ m^2	[Athena, 2000]
Roof			
Second floor ceiling			
Thermal insulation (0.4 m cellulose)	7 956	4.4/ kg	[Alcorn, 1998]
Vapor barrier (polyethylene 6 mm)	502	5/ m^2	[Athena, 2000]
Sheathing	6 460	64.3/ m^2	[Athena, 2000]
Furring 1x4 @ 0.6 m c.c.	2 370	23.59/ m^2	[Athena, 2000]
Gypsum board	5 475	47/ m^2	[Athena, 2000]
Pitched roof			
Asphalt shingles	36 960	280/ m^2	[Buchanan, 1998]
Water proof (bitumen)	5 995	45420/ m^3	[Alcorn, 1998]
Wood truss + plywood deck	18 256	138.3/ m^2	[Athena, 2000]

Floors			
Ground floor			
Finishing (wooden floor)	7 431	8330/ m^3	[Alcorn, 1998]
Floor painting	2 275	127500/ m^3	[Alcorn, 1998]
Wood truss + plywood deck	15 938	170/ m^2	[Athena, 2000]
Furring 1x4 @ 0.6 m c.c.	2 907	23.59/ m^2	[Athena, 2000]
Gypsum board	4 193	47/ m^2	[Athena, 2000]
Second floor			
Finishing (wooden floor)	7 238	8330/ m^3	[Alcorn, 1998]
Floor painting	2 216	127500/ m^3	[Alcorn, 1998]
Wood truss + plywood deck	15 556	170/ m^2	[Athena, 2000]
Thermal insulation (0.1 m cellulose)	1 720	4.4/ kg	[Alcorn, 1998]
Vapor barrier (polyethylene 6 mm)	434	5/ m^2	[Athena, 2000]
Sheathing	5 588	64.3/ m^2	[Athena, 2000]
Furring 1x4 @ 0.6 m c.c.	2 050	23.59/ m^2	[Athena, 2000]
Gypsum board	4 736	47/ m^2	[Athena, 2000]
Interior partitions:			
Gypsum board	23 380	47/ m^2	[Athena, 2000]
Wood suds 2x4 @ 0.6 m c.c.	6 929	32.3/ m^2	[Athena, 2000]
Windows and doors			
Exterior windows			
Double glazing	9 294	40060/ m^3	[Alcorn, 1998]
Fiberglass frame	27 904	93620/ m^3	[Alcorn, 1998]
Exterior doors			
Steel cladding	3 713	135/ m^2	[Athena, 2000]
Steel sections	3 141	69790/ m^3	[Alcorn, 1998]
Thermal insulation (0.05 m polystyrene)	965	117/ kg	[Alcorn, 1998]
Interior doors			
Plywood	11 041	9440/ m^3	[Buchanan, 1998]
Hardwood sections	4 950	20626/ m^3	[Baird, 1983]
Finishes			
Painting (water based emulsion)	23 198	115000/ m^3	[Alcorn, 1998]
Total	707863		

The operating energy of the base case

The operating energy term is used to represent the energy consumption for heating, cooling and the base load including the domestic hot water, cooking and electrical appliances. The base load was assumed to be the same for the base case and the selected design alternatives. Therefore, only the operating energy was used to compare the energy efficiency of the base case and the design alternatives.

The energy consumption for cooling was not evaluated, as it is out of scope of this study. The simulation results revealed that the yearly energy consumption for heating for the base case is 10470 kWh or 34 kWh/m^2 of floor area. The heating consumption of the selected design alternatives has been evaluated in chapter 5 by using BLAST program.

6.1.2 Life-cycle analysis of cost

The life-cycle analysis of cost is an effective method used to assess the total cost of the design alternatives, comprising the initial cost for the building materials and construction; and the operating cost. The operating cost includes the energy and maintenance costs during the life of the building in addition to the demolishing cost at the end of the building age. The maintenance and demolishing costs were assumed to be similar for the base case and design alternatives; only the cost of operating energy for the base case and its related alternatives was considered.

Initial cost of the base case

The initial cost of the base case was evaluated by using Means Coast Data (2001), including the total cost of building materials, labor, contractor profit and overhead costs. Seven categories for the initial cost of the base case were identified including: site work, floors, building envelope, roof, interior partitions, windows and doors and finishing. As the cost of the base case was obtained from the assemblies and materials tables listed in the Means (2001), calculated in US dollars, a changing factor of 1.60 was used to change the cost from US dollars to Canadian dollars, as shown in table 6.2.

Table 6.2. Initial cost of the base case

Parameters	Cost		Percentage
	[CAD $]	[CAD $/ m^2]	[%]
Site work			
Foundations	18 594	60.1	8.56
Slab on grade	7 083	22.9	3.26
Floors			
Ground floor	14 254	46.1	6.56
First floor	15 691	50.7	7.22
Building envelope			
Basement exterior walls	39 913	129	18.37
Above ground walls	64 016	206.8	29.46
Roof			
Second floor ceiling	7 194	23.2	3.31
Pitched roof	11 734	37.9	5.40
Interior partitions			
Gypsum board partitions	10 192	32.9	4.69
Windows and doors			
Exterior windows	11 288	36.5	5.20
Exterior doors	2 904	9.4	1.34
Interior doors	4 813	15.6	2.22
Finishing			
Painting	9 590	31	4.41
Total	217 266	702	100

Operating cost of the base case

The operating cost includes the energy cost and maintenance cost during the lifetime of the building along with the demolishing cost at the end of the building life. For this study, only the cost of the energy consumption for heating was considered. The yearly heating consumption was assumed to be constant during the lifetime of the building. For instance, the heating consumption for the base case was 10470 kWh; then the heating during 30 years is equal to: 10470 * 30 = 314100 kWh.

The heating cost was calculated with respect to the electricity rate of Hydro-Quebec (1998) as follows:

1- $ 0.39 as a fixed charge per day; plus

2- $ 0.0474 per kilowatt-hour for first 30 kilowatt-hour per day; plus

3- $ 0.0597 per kilowatt-hour for the remaining consumption, which exceed 30 kilowatt-hour per day or 10950 kilowatt-hour per year.

The present worth method (PW) was used to evaluate the present value of money (PV) for the heating cost over the life cycle of the building. The following formula (Model National Energy Code of Canada, 1997) was applied:

$$PW_j = C_j * (1 - (1 + a)^{-n''}) / a \qquad (6.1)$$

where:

C_j = the annual heating cost for alternative j in the first year:

a = the effective interest rate = $(i\text{-e})/(1\text{+e})$;

e = the rate at which energy costs are expected to increase (energy acceleration rate); and

i = the discount rate or cost of money including the inflation; and

n'' = planning horizon.

For example, assuming that the life cycle of the base case is 30 years with annual interest rate of 5% and energy acceleration rate of 0.0%, then the present value of the heating cost for the base case over the life span of 30 years can be calculated as follows:

731.23 (the heating cost for the first year) * $[1- (1+ 0.05)^{-30}]/ 0.05$ = $ 11241, whereas the effective interest rate a is equal to (0.05- 0.0)/ (1+ 0.0) = 0.05.

The value of money (PV) was used in the decision support system to assess the cost-effectiveness for the base case and design alternatives during the building lifetime. The values of the life cycle, annual interest rate and the energy acceleration rate are defined by the user of the decision support system. The initial cost for the selected design alternatives was calculated similarly to the procedures used to calculate the initial and operating costs of the base case.

6.1.3 The environmental impact

Global atmospheric issues have been the major concern of the environmental scientists in the last decade. Two main issues were identified: the global warming and the ozone layer depletion. Global warming is due to the hazard gases, defined later and also carbon dioxide accumulations in the lower atmosphere acting as greenhouse warming gases. The depletion of the stratosphere, which is known as the ozone hole to the public, is due to the photochemical release of chlorine in the atmosphere from refrigerant (CFCs) gases, discharged at the surface and migrates upwards causing more destroying of ozone.

Hazard gases were classified (Thomas, R. 1999) as follows: (i) CFCs are related to chloroflurocarbon, which consists of organic molecule with chlorine and fluorine atoms; (ii) HCFCs are hydrochloroflurocarbons including chlorine and have lower atmospheric lifetimes than CFCs; (iii) HFCs are hydrofluorocarbons including chlorine but have a negligible effect on ozone layers; and (iv) Halon is referred to all Halo-generated hydrocarbon.

Although most of previous substances are more harmful than CO_2, they have less impact on the global warming as they are produced in small amounts with respect to CO_2 emissions. Scientists assume that most of the environmental problems nowadays are due to global warming and ozone depletion.

The impact of greenhouse gases on the environment are calculated by using the pollutant coefficient evaluated by Buhl, F. (1998) and the Global Warming Potential (GWP) index, presented by Master, G. (1998), as shown in table 6.3.

Table 6.3. Pollutants coefficients and Global Warming Potential (GWP) index

Greenhouse gas	Pollutants coefficient [g/kWh]		Global Warming Potential for a time horizon in years		
	Oil	Natural gas	20 years	100 years	500 years
Carbon dioxide (CO_2)	263	178	1	1	1
Nitrous oxide (N_2O)	0.56764	0.212	280	310	170

The pollutant coefficient index is used to calculate the amount of hazard gases emitted due to the use of heating oil and natural gases. In addition, the GWP is a weighting factor for greenhouse gases that enables comparisons between the impact of any greenhouse gas and CO_2 on the global warming during a specified time horizon. For instance, 1 kg of N_2O emitted today (Table 6.3) will have the same impact over the next 100 years as the release of 310 kg of CO_2 today. However, due to the lack of information of both pollutants coefficient and GWP for measured greenhouses gases, only the carbon dioxide CO_2 and Nitrous oxide N_2O were used to assess the equivalent CO_2 emissions in this study.

For instance, the embodied energy of the base case house was estimated at 196.629 kWh (Table 6.1). Assuming the time horizon is 100 year; and 50% of the embodied energy is produced from natural gas while the remaining part was from oil, then the calculations of equivalent CO_2 emissions due to embodied energy of the base case are as follows:

1- Mass of CO_2 emissions:

0.5 (263 * 196629) + 0.5 (178 * 196629) = 43.36 tons of CO_2

2- Mass of N_2O emissions:

0.5 (0.56764 * 196629) + 0.5 (0.212 * 196629) = 0.0766 ton of N_2O

By using the pollutants mass of CO_2 and N_2O emissions and GWP indices, the total equivalent CO_2 emissions are calculated.

1- CO_2 emissions: (43.36 * 1) = 43.36 tons of CO_2 emissions

2- Equivalent CO_2 due to N_2O emissions: (0.0766 * 310) = 23.75 tons of CO_2 emissions

Thus the total GWP for equivalent CO_2 emissions due to embodied energy is equal to:

43.36 + 23.75 = 67.11 tons of CO_2 emissions.

Similarly, the equivalent CO_2 emissions due to the operating energy for the base case were assessed, whereas the yearly energy consumption for heating is 10470 kWh. The hydro-electricity in Quebec accounts for almost 97% of electricity used in the residential sector. It is generally assumed that the generation of hydro-electricity does not produce any of greenhouse gases.

It is assumed that 3% of heating consumption was from off-site thermal generating plants using 100% heating oil or natural gas, while the remaining part of heating consumption is produced by hydro-electricity. Following the similar procedures for the GWP of embodied energy calculations, then the equivalent CO_2 emissions due to operating energy of the base case for a life cycle of 30 years are as follows:

1- Mass of CO_2 emissions:

0.03 (178 * 10470 * 30) = 1.68 tons of CO_2

2- Mass of N_2O emissions:

0.03 (0.212 * 10470 * 30) = 0.002 ton of N_2O

By using the pollutants mass of CO_2 and N_2O emissions and GWP indices, the total equivalent CO_2 emissions are calculated.

1- CO_2 emissions: (1.68 * 1) = 1.68 tons of CO_2 emissions

2- Equivalent CO_2 due to N_2O emissions: (0.002 * 310) = 0.62 ton of CO_2 emissions

Thus the total GWP for equivalent CO_2 emissions due to operating energy is equal to:

1.68 + 0.62 = 2.3 tons of CO_2 emissions.

The total GWP for equivalent CO_2 emissions due to the embodied energy and operating energy of the base case is equal to:

67.11 + 2.3 = 69.41 tons of CO_2 emissions.

6.1.4 Life-cycle analysis of the selected design alternatives

In this chapter, the design alternatives were selected on the basis of the parametric approach, described in chapter 5, including the modifications of: (i) the characteristics of building envelope, (ii) the architectural design, and (iii) the thermostat setpoint for heating. These design alternatives have been used to establish the decision support system. The building form and presence of attached buildings, in addition to the non-parametric design alternatives were not addressed for the decision support system, as many restrictions such as related-provincial regulations, occupants preferences, site dimensions and urban planning limit the exploit of such alternatives.

Only the design alternatives, which have the minimum and maximum impact on the energy consumption of the base case house, were used in this section. This approach is used to represent the range between the minimum and maximum effect of the design alternatives values, and to reduce the number of alternatives used to establish the decision support system. The value having a minimum impact on the energy consumption increase with respect to the energy consumption of the base case is expressed by the term of "minimum design alternative", while the value having a maximum impact on the increase of energy consumption is expressed by the term of "maximum design alternative". For instance, the minimum value for the alternative of the thermal resistance of windows is 0.88 $m^2.{}^oC/W$ (Table 6.4), which have the minimum impact on energy consumption increase of the base case (9366 kWh). This alternative is expressed by the term of minimum design alternative.

Table 6.4. Minimum and maximum values of the selected design alternatives

Design alternatives	Abbreviation	Operating energy	
		Heating consumption [kWh/ year]	Reduction percentage [%]
Base case house	Base case	10 470	0.0
Thermal resistance of basement, above ground walls and roof [m^2·°C/W]:			
Basement walls:			
2.2	Alt2	12 090	-15.5
8.8	Alt3	9 606	+8.25
Above ground walls:			
3.4	Alt4	12 270	-17.2
10.57	Alt5	8 943	+14.6
Roof:			
5.3	Alt6	11 180	-6.8
17.6	Alt7	10 160	+3
Total thermal resistance of basement, above ground walls and roof:			
2.2; 3.4 and 5.3	Alt8	14 610	-39.5
8.8; 10.57 and 17.61	Alt9	7 775	+25.7
Thermal resistance for windows [m^2·°C/W]:			
0.36 (double-glazed window)	Alt10	12 140	-16
0.88 (triple-glazed window)	Alt11	9 366	+10.5
Airtightness [ach]:			
0.6	Alt12	8 612	+17.7
3	Alt13	15 860	-51.5
Movable insulation on windows [m^2·°C/W]:			
0.0	Base case	10 470	0.0
8.8	Alt14	9 918	+5.3
Thermal mass walls [%]:			
External basement walls:			
50	Alt15	10 470	0.0
250	Alt16	10 470	0.0
External above ground walls:			
50	Alt17	10 470	0.0
250	Alt18	10 470	0.0
Internal basement walls:			
50	Alt19	10 440	+0.3
250	Alt20	10 410	+0.57
Internal above ground walls:			
50	Alt21	10 410	+0.57
250	Alt22	10 210	+2.5

Solar absorptivity coefficient:			
External walls:			
0.10 (extremely light color)	Alt23	10 670	-1.9
0.90 (extremely dark color)	Alt24	10 420	+0.5
Internal walls:			
0.10	Alt25	10 820	-3.3
0.90	Alt26	10 440	+0.3
External and internal walls:			
0.10	Alt27	11 030	-5.3
0.90	Alt28	10 390	+0.8
Glazing-to-wall percentage [%]:			
Northern facade (N):			
0.0	Alt29	10 290	+1.7
39	Alt30	11 070	-5.7
Eastern facade (E):			
1.0	Base case	10 470	0.0
40	Alt31	11 010	-5.2
Western facade (W):			
2.0	Base case	10 470	0.0
40	Alt32	10 810	-3.2
Southern facade (S):			
0.0	Alt33	11 360	-8.5
60	Alt34	9 668	+7.7
Total Glazing-to-wall percentage:			
N= 39; E= 1.0; W=2.0 and S= 0.0	Alt35	12 990	-24
N= 0.0; E= 1.0; W=2.0 and S= 60	Alt36	9 455	+9.7
Rotation angle [°]:			
0.0	Base case	10 470	0.0
90	Alt37	11 380	-8.7
Setpoint heating temperature [°C]:			
17°C at day and 14°C at night	Alt38	6 832	+34.7
24°C at day and 21°C at night	Alt39	13 510	-29

The life-cycle performance of each design alternative, as presented in table 6.5 was evaluated based on the following assumptions: (i) the life of house is 30 years, (ii) the interest rate including inflation is 5%, and (iii) the energy escalation rate is 0%. For the environmental impact, calculated in terms of equivalent CO_2 emissions, 3% of heating consumption was assumed to be from off-site generated electricity produced by thermal generating plants using heating oil and natural gas.

The remaining part of heating consumption is produced by hydro-electricity. It was also assumed that 50% of embodied energy comes from natural gas and 50% comes from oil. Table 6.5 illustrates the life-cycle analysis of the design alternatives. However, the user of the decision support system presented in section 6.3, can input his/her own economic data and contribution of energy sources.

Table 6.5. Life-cycle analysis of design alternatives

Alt. number	Initial cost [1000$]	Yearly operating cost [1000$]	Life-cycle cost (LCC) [1000$]	Embodied energy [1000 kWh]	Yearly operating energy [1000 kWh]	Life-cycle energy (LCE) [1000 kWh]	Equivalent CO_2 emissions [ton]
Base case	217.27	0.731	228.51	196.63	10.47	510.73	69.42
Alt2	214.63	0.835	227.47	194.90	12.09	557.60	69.18
Alt3	220.62	0.684	231.14	198.75	9.61	486.93	69.95
Alt4	210.34	0.848	223.37	185.00	12.27	553.10	65.84
Alt5	223.28	0.648	233.24	200.71	8.94	469.00	70.47
Alt6	215.86	0.773	227.75	195.52	11.18	530.92	69.20
Alt7	219.03	0.714	230.01	198.01	10.16	502.81	69.82
Alt8	206.30	1.007	221.79	182.16	14.61	620.46	65.39
Alt9	228.39	0.585	237.39	204.21	7.78	437.46	71.42
Alt10	215.19	0.839	228.08	196.63	12.14	560.83	69.78
Alt11	224.40	0.671	234.72	199.22	9.37	480.20	70.06
Alt12	217.27	0.630	226.96	196.63	8.61	454.99	69.01
Alt13	217.27	1.093	234.07	196.63	15.86	672.43	70.60
Alt14	226.31	0.701	237.09	207.76	9.92	505.30	73.10
Alt15	208.74	0.731	219.98	193.48	10.47	507.58	68.34
Alt16	238.56	0.731	249.80	238.60	10.47	552.70	83.74
Alt17	208.72	0.731	219.96	186.63	10.47	500.73	66.01
Alt18	239.13	0.731	250.37	346.43	10.47	660.53	120.55
Alt19	208.74	0.730	219.96	193.48	10.44	506.68	68.34
Alt20	238.56	0.728	249.75	238.60	10.39	550.30	83.73
Alt21	208.72	0.728	219.91	186.63	10.41	498.93	65.99
Alt22	239.13	0.717	250.16	346.43	10.21	652.73	120.50
Alt23	217.27	0.742	228.67	196.63	10.67	516.73	69.46
Alt24	217.27	0.729	228.47	196.63	10.42	509.23	69.41
Alt25	217.27	0.750	228.80	196.63	10.82	521.23	69.49

Alt26	217.27	0.730	228.48	196.63	10.44	509.83	69.41
Alt27	217.27	0.763	228.99	196.63	11.03	527.53	69.54
Alt28	217.27	0.727	228.44	196.63	10.39	508.33	69.40
Alt29	214.02	0.721	225.12	194.07	10.29	502.77	68.50
Alt30	228.38	0.765	240.14	205.40	11.07	537.50	72.54
Alt31	230.94	0.761	242.64	207.43	11.01	537.73	73.22
Alt32	230.94	0.750	242.46	207.43	10.81	531.73	73.18
Alt33	208.29	0.785	220.36	189.54	11.36	530.34	67.19
Alt34	236.00	0.688	246.57	211.43	9.67	501.47	74.29
Alt35	219.40	0.897	233.19	198.31	12.99	588.01	70.55
Alt36	232.76	0.676	243.15	208.87	9.46	492.52	73.37
Alt37	217.27	0.787	229.36	196.63	11.38	538.03	69.62
Alt38	217.27	0.534	225.47	196.63	6.83	401.59	68.62
Alt39	217.27	0.932	231.60	196.63	13.51	601.93	70.08

A large variation was noticed between the results of the life-cycle analysis for the design alternatives. Five parameters with the most impact on the energy consumption relative to the base case, are identified: the thermal resistance of building envelope; thermal resistance of windows; glazing-to-wall ratio; airtightness; and the setpoint heating temperature. The values of design alternatives, which have the minimum and maximum impact on the energy consumption of the base case, were identified. Then the combination between the minimum and maximum values of design alternatives were established to address the overall impact of combined alternatives on the base case energy performance. Table 6.6 presents the values corresponding to the minimum and maximum impact of the best alternatives.

Table 6.6. Minimum and maximum values of the best design alternatives

Parameters	Yearly heating consumption [kWh]
Thermal resistant of basement, above ground walls and roof [$m^2 \cdot {}^oC/W$]:	
2.2, 3.4 and 5.3 (maximum)	14 610
8.8, 10.57, 17.61 (minimum)	7 775
Thermal resistance for windows [$m^2 \cdot {}^oC/W$]:	
0.36 (maximum)	12 140
0.88 (minimum)	9 366
Glazing-to-wall percentage for north (N); east (E); west (W) and south (S) facades [%]:	
N= 39, E= 1.0, W=2.0, S= 0.0 (maximum)	12 990
N= 0.0, E= 1.0, W=2.0, S= 60 (minimum)	9 455
Airtightness [ach]:	
3 (maximum)	15 860
0.6 (minimum)	8 612
Setpoint heating temperature [°C]:	
24°C at day and 21°C at night (maximum)	13 510
17°C at day and 14°C at night (minimum)	6 832

6.2 Combinations between the design alternatives

Combinations between the minimum values and maximum values of the best design alternatives (Table 6.6) for two parameters were proposed, establishing the two-parameter combinations. For instance, the maximum value (3 ach, Table 6.6) for the airtightness parameter was combined with the maximum value for the parameter of thermal resistance of windows (0.36 $m^2 \cdot {}^oC/W$, Table 6.6) composing a two-parameter alternative. This alternative has the maximum impact on the energy consumption increase with respect to the energy consumption of the base case (10470 kWh). Combinations between the design alternatives were proposed, first in pairs, then in-groups of three and four, and finally all the five parameters. Table 6.7 presents the description for the design alternatives of two-combinations.

Table 6.7. Two-parameter combinations of design alternatives

Design alternatives	Abbreviation
Combination no. 1 Thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Thermal resistance of windows [$m^2 \cdot {}^oC/W$]:	
A- (2.2, 3.4, 5.30) and (0.36)	Alt40
B- (8.8, 10.57, 17.61) and (0.88)	Alt41
Combination no. 2 Thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Glazing-to-wall ratio [%]:	
A- (2.2, 3.4, 5.30) and (N= 39, E=1, W=2, S=0)	Alt42
B- (8.8, 10.57, 17.61) and (N=0, E=1, W=2, S=60)	Alt43
Combination no. 3 Thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Setpoint heating temperature [^oC]:	
A- (2.2, 3.4, 5.30) and (24 at day, 21 at night)	Alt44
B- (8.8, 10.57, 17.61) and (17 at day, 14 at night)	Alt45
Combination no. 4 Thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (3.0)	Alt46
B- (8.8, 10.57, 17.61) and (0.6)	Alt47
Combination no. 5 Thermal resistance of windows [$m^2 \cdot {}^oC/W$] and Glazing-to-wall ratio [%]:	
A- (0.36) and (N=39, E=1, W=2, S=0)	Alt48
B- (0.88) and (N=0, E=1, W=2, S=60)	Alt49
Combination no. 6 Thermal resistance of windows [$m^2 \cdot {}^oC/W$] and Setpoint heating temperature [^oC]:	
A- (0.36) and (24 at day, 21 at night)	Alt50
B- (0.88) and (17 at day, 14 at night)	Alt51
Combination no. 7 Thermal resistance of windows [$m^2 \cdot {}^oC/W$] and Airtightness [ach]:	
A- (0.36) and (3.0)	Alt52
B- (0.88) and (0.6)	Alt53
Combination no. 8 Glazing-to-wall ratio [%] and Setpoint heating temperature [^oC]:	
A- (N=39, E=1, W=2, S=0) and (24 at day, 21 at night)	Alt54
B- (N=0, E=1, W=2, S=60) and (17 at day, 14 at night)	Alt55
Combination no. 9 Glazing-to-wall ratio [%] and Airtightness [ach]:	
A- (N=39, E=1, W=2, S=0) and (3.0)	Alt56
B- (N=0, E=1, W=2, S=60) and (0.6)	Alt57

Combination no. 10 Set point heating temperature [°C] and Airtightness [ach]: A- (24 at day, 21 at night) and (3.0) B- (17 at day, 14 at night) and (0.6)	 Alt58 Alt59

The Life-Cycle Analysis (LCA) approach was used to estimate the overall impact of such alternatives. The similar assumptions and procedures used for the design alternatives (Table 6.5) were applied for the combinations of alternatives.

Table 6.8. LCA for two-parameter combinations of the design alternatives

Alt. Number	Initial cost [1000$]	Yearly operating cost [1000$]	Life-cycle cost (LCC) [1000$]	Embodied energy [1000 kWh]	Yearly operating energy [1000 kWh]	Life-cycle energy (LCE) [1000 kWh]	Equivalent CO_2 emissions [ton]
Alt40	204.22	1.120	221.45	182.16	16.26	669.96	65.75
Alt41	235.53	0.525	243.60	206.80	6.67	407.02	72.06
Alt42	208.44	1.135	225.89	183.85	16.48	678.25	66.37
Alt43	243.89	0.544	252.25	216.45	7.02	427.11	75.43
Alt44	206.30	1.264	225.73	182.16	18.36	732.96	66.21
Alt45	228.39	0.424	234.91	204.21	4.80	348.27	70.76
Alt46	206.30	1.379	227.51	182.16	20.05	783.66	66.58
Alt47	228.39	0.486	235.87	204.21	5.96	383.01	71.02
Alt48	217.32	1.210	235.92	198.31	17.57	725.41	71.55
Alt49	239.89	0.594	249.02	211.45	7.94	449.50	73.92
Alt50	215.19	1.063	231.53	196.63	15.42	659.23	70.50
Alt51	224.40	0.487	231.88	199.22	5.96	378.14	69.31
Alt52	215.19	1.208	233.76	196.63	17.55	723.13	70.97
Alt53	224.40	0.571	233.17	199.22	7.52	424.73	69.65
Alt54	219.40	1.149	237.06	198.31	16.68	698.71	71.36
Alt55	232.76	0.486	240.22	208.87	5.95	387.22	72.60
Alt56	219.40	1.266	238.86	198.31	18.39	750.01	71.73
Alt57	232.76	0.579	241.66	208.87	7.67	438.88	72.98
Alt58	217.27	1.375	238.40	196.63	19.98	796.03	71.50
Alt59	217.27	0.460	224.33	196.63	5.47	360.61	68.32

Table 6.9 presents the description for the design alternatives of three-combinations.

Table 6.9. Three-parameter combinations of the design alternatives

Design alternatives	Abbreviation
Combination no. 1 Thermal resistance of exterior walls and roof [m^2·°C/W] and Thermal resistance of windows [m^2·°C/W] and Glazing-to-wall ratio [%]:	
A- (2.2, 3.4, 5.30) and (0.36) and (N=39, E=1, W=2, S=0)	Alt60
B- (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60)	Alt61
Combination no. 2 Thermal resistance t of exterior walls and roof [m^2·°C/W] and Thermal resistance of windows [m^2·°C/W] and Setpoint heating temperature [°C]:	
A- (2.2, 3.4, 5.30 and (0.36) and (24 at day, 21 at night)	Alt62
B- (8.8, 10.57, 17.61) and (0.88) and (17 at day, 14 at night)	Alt63
Combination no. 3 Thermal resistance of exterior walls and roof [m^2·°C/W] and Thermal resistance of windows [m^2·°C/W] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30 and (0.36) and (3.0)	Alt64
B- (8.8, 10.57, 17.61) and (0.88) and (0.6)	Alt65
Combination no. 4 Thermal resistance t of exterior walls and roof [m^2·°C/W] and Glazing-to-wall ratio [%]and Setpoint heating temperature [°C]:	
A- (2.2, 3.4, 5.30) & (3.0) and (24 at day, 21 at night)	Alt66
B- (8.8, 10.57, 17.61) & (0.6) and (17 at day, 14 at night)	Alt67
Combination no. 5 Thermal resistance of exterior walls and roof [m^2·°C/W] and Glazing-to-wall ratio [%] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (N=39, E=1, W=2, S=0) and (3.0)	Alt68
B- (8.8, 10.57, 17.61) and (N=0, E=1, W=2, S=60) and (0.6)	Alt69
Combination no. 6 Thermal resistance of exterior walls and roof [m^2·°C/W] and Setpoint heating temperature [°C] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (24 at day, 21 at night) and (3.0)	Alt70
B- (8.8, 10.57, 17.61) and (17 at day, 14 at night) and (0.6)	Alt71
Combination no. 7 Thermal resistance of windows [m^2·°C/W] and Glazing-to-wall ratio [%] and Setpoint heating temperature [°C]:	
A- (0.36) and (N=39, E=1, W=2, S=0) and (24 at day, 21 at night)	Alt72
B- (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night)	Alt73
Combination no. 8 Thermal resistance of windows [m^2·°C/W] and Glazing-to-wall ratio [%] and Airtightness [ach]:	
A- (0.36) and (N=39, E=1, W=2, S=0) and (3.0)	Alt74
B- (0.88) and (N=0, E=1, W=2, S=60) and (0.6)	Alt75

Combination no. 9 Thermal resistance of windows [m^2·°C/W] and Setpoint heating temperature [°C] and Airtightness [ach]:	
A- (0.36) and (24 at day, 21 at night) and (3.0)	Alt76
B- (0.88) and (17 at day, 14 at night) and (0.6)	Alt77
Combination no. 10 Glazing-to-wall ratio [%] and Setpoint heating temperature [°C] and Airtightness [ach]:	
A- (N=39, E=1, W=2, S=0) and (24 at day, 21 at night) and (3.0)	Alt78
B- (N=0, E=1, W=2, S=60) and (17 at day, 14 at night)and (0.6)	Alt79

Table 6.10. LCA for three-parameter combinations of the design alternatives

Alt. Number	Initial cost [1000$]	Yearly operating cost [1000$]	Life-cycle cost (LCC) [1000$]	Embodied energy [1000 kWh]	Yearly operating energy [1000 kWh]	Life-cycle energy (LCE) [1000 kWh]	Equivalent CO$_2$ emissions [ton]
Alt60	206.36	1.446	228.58	183.85	21.02	814.45	67.37
Alt61	251.02	0.461	258.11	219.04	5.50	383.89	75.98
Alt62	204.22	1.393	225.64	182.16	20.25	789.66	66.62
Alt63	235.53	0.378	241.33	206.80	3.96	325.54	71.46
Alt64	204.22	1.493	227.18	182.16	21.72	833.76	66.95
Alt65	235.53	0.428	242.11	206.80	4.89	353.53	71.67
Alt66	208.44	1.446	230.67	183.85	21.03	814.75	67.37
Alt67	243.89	0.389	249.87	216.45	4.16	341.37	74.80
Alt68	208.44	1.509	231.63	183.85	21.94	842.05	67.57
Alt69	243.89	0.452	250.83	216.45	5.32	376.08	75.05
Alt70	206.30	1.720	232.74	182.16	25.03	933.06	67.67
Alt71	228.39	0.353	233.82	204.21	3.50	309.12	70.48
Alt72	217.32	1.535	240.92	198.31	22.33	868.21	72.59
Alt73	239.89	0.427	246.45	211.45	4.86	357.25	73.25
Alt74	217.32	1.594	241.83	198.31	23.19	894.01	72.78
Alt75	239.89	0.499	247.56	211.45	6.19	397.06	73.54
Alt76	215.19	1.509	238.39	196.63	21.95	855.13	71.94
Alt77	224.40	0.413	230.75	199.22	4.61	337.64	69.02
Alt78	219.40	1.595	243.91	198.31	23.20	894.31	72.79
Alt79	232.76	0.416	239.16	208.87	4.67	348.91	72.32

Similarly, the combinations between design alternatives for four and five groups were proposed, as shown in table 6.11.

Table 6.11. Four-parameter and five-parameter combinations for design alternatives

Design alternatives	Abbreviation
Combination no. 1 Thermal resistance of exterior walls and roof [m^2·^{o}C/W] and Thermal resistance of windows [m^2·^{o}C/W] and Glazing-to-wall ratio [%] and Setpoint heating temperature [^{o}C]:	
A- (2.2, 3.4, 5.30) and (0.36) and (N=39, E=1, W=2, S=0) and (24 at day, 21 at night)	Alt80
B- (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night)	Alt81
Combination no. 2 Thermal resistance of exterior walls and roof [m^2·^{o}C/W] and Thermal resistance of windows [m^2·^{o}C/W] and Glazing-to-wall ratio [%] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (0.36) and (N=39, E=1, W=2, S=0) and (3.0)	Alt82
B- (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60) and (0.6)	Alt83
Combination no. 3 Thermal resistance of exterior walls and roof [m^2·^{o}C/W] and Glazing-to-wall ratio [%] and Setpoint heating temperature [^{o}C] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (N=39, E=1, W=2, S=0) and (24 at day, 21 at night) and (3.0)	Alt84
B- (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night) and (0.6)	Alt85
Combination no. 4 Thermal resistance of windows [m^2·^{o}C/W] and Glazing-to-wall ratio [%] and Setpoint heating temperature [^{o}C] and Airtightness [ach]:	
A- (0.36) and (N=39, E=1, W=2, S=0) and (24 at day, 21 at night) and (3.0)	Alt86
B- (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night) and (0.6)	Alt87
Combination no. 5 (Five- parameter combination) Thermal resistance of exterior walls and roof [m^2·^{o}C/W] and Thermal resistance of windows [m^2·^{o}C/W] and Glazing-to-wall ratio [%] and Setpoint heating temperature [^{o}C] and Airtightness [ach]:	
A- (2.2, 3.4, 5.30) and (0.36) and (N=39, E=1, W=2, S=0) and (24 at day, 21 at night) and (3.0)	Alt88
B- (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night) and (0.6)	Alt89

Table 6.12. LCA for four-parameter and five-parameter combinations

Alt. Number	Initial cost [1000$]	Yearly operating cost [1000$]	Life-cycle cost (LCC) [1000$]	Embodied energy [1000 kWh]	Yearly operating energy [1000 kWh]	Life-cycle energy (LCE) [1000 kWh]	Equivalent CO_2 emissions [ton]
Alt80	206.36	1.821	234.35	183.85	26.51	979.15	68.57
Alt81	251.02	0.335	256.17	219.04	3.17	314.14	75.47
Alt82	206.36	1.835	234.57	183.85	26.72	985.45	68.62
Alt83	251.02	0.380	256.86	219.04	4.00	338.95	75.65
Alt84	208.44	1.884	237.41	183.85	27.44	1007.05	68.78
Alt85	243.89	0.326	248.91	216.45	3.01	306.81	74.55
Alt86	217.32	1.985	247.84	198.31	28.91	1065.61	74.04
Alt87	239.89	0.360	245.42	211.45	3.63	320.38	72.98
Alt88	206.36	2.280	241.40	183.85	33.22	1180.45	70.05
Alt89	251.02	0.275	255.24	219.04	2.06	280.87	75.22

Results from the LCA of the design alternatives (Tables 6.5, 6.8, 6.10, and 6.12) reveal that most of the alternatives have a considerable impact on the energy performance of the base case house. Some of the selected design alternatives are not cost-effective today, because the present house is already energy-efficient, and the electricity cost charged by the utility companies is relatively low. However, on the medium or long term some of these design alternatives might become more attractive, if energy cost increases, or the tax credits for CO_2 emissions is eventually implemented in Canada.

The information of the LCA for the design alternatives and combination between alternatives were used to build the database on which the decision support system is based.

6.3 The decision support system

The Decision Support System (DSS) is used to support the complex decision-making and problem solving. Over the past three decades, many researches have emerged to assist decision makers faced with specific kind of problems. Research in this area focused on how information technology can improve the efficiency with which a user makes a decision and can improve the effectiveness of that decision.

For this study, the DSS was developed by using the Microsoft Excel program comprising:

1- The database section including the information about the base case and design alternatives (e.g., life-cycle energy, life-cycle cost and equivalent CO_2).

2- The interface section, which enables the user to input the information, required for the analysis (e.g., life span of the house, interest rate); this section also presents the results.

3- The modeling functions with access to both database and interface sections to transfer and perform the commands inserted by the users.

The methodology used to build the DSS was based on the life-cycle analysis, including the life-cycle cost, life-cycle energy and equivalent CO_2 emissions for the base case house and its selected design alternatives. The information for the life-cycle analysis of the base case, and selected design alternatives was obtained from previous sections of this chapter. Figure 6.1 illustrates the structure of the Decision Support System (DSS).

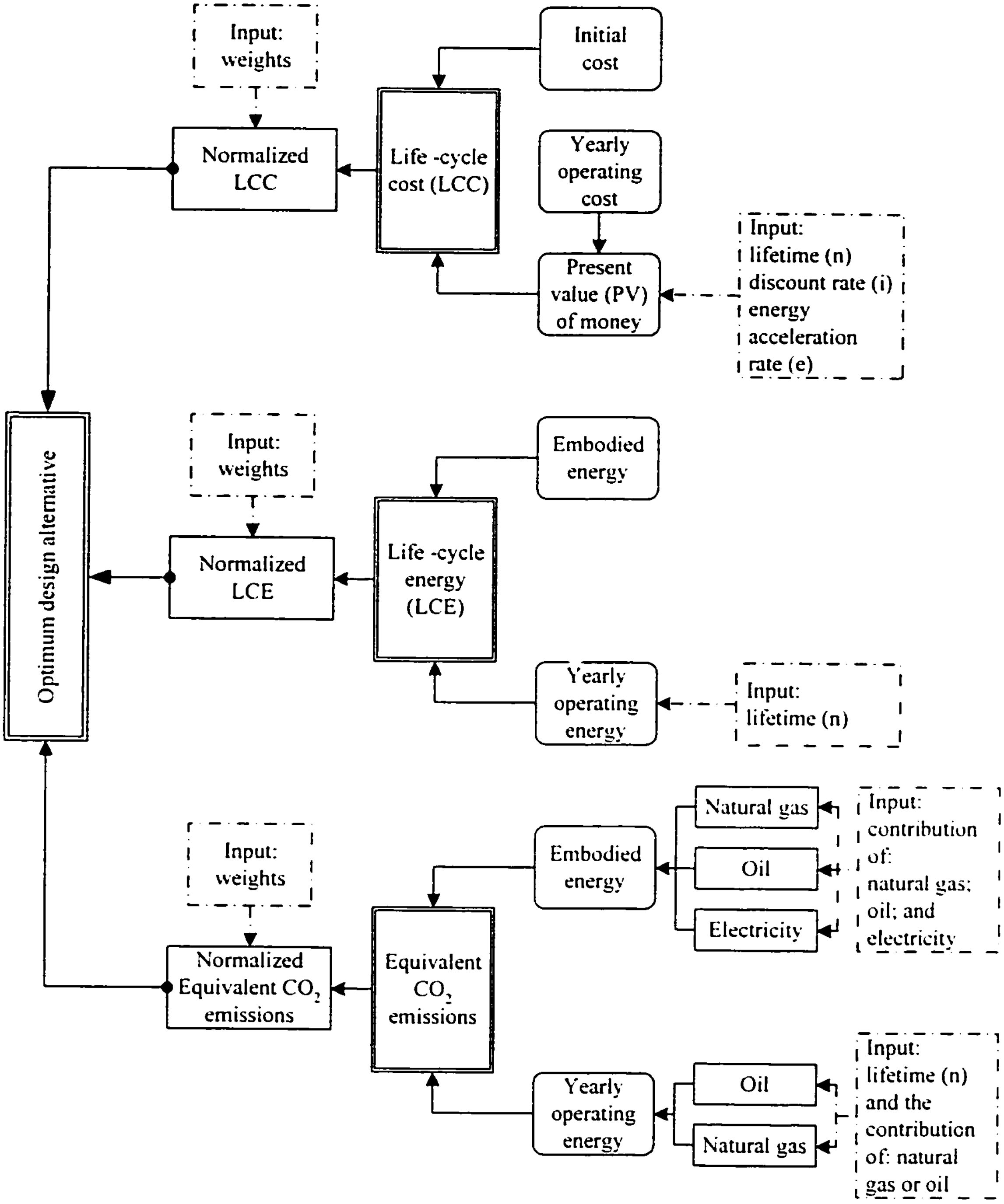


Figure 6.1. Flowchart of the decision support system

Life-cycle analysis

The initial cost and yearly operating cost for the base case and design alternatives were calculated and input in the database section of the DSS. Then the present worth method was applied to calculate the present value of the operating cost over the life cycle of building. The information of the lifetime of the building, annual discount rate and energy acceleration rate, are provided by the system user.

The initial or embodied energy and the yearly operating energy for heating of the base case and selected design alternatives were calculated and added to the database section of the DSS. Using the information provided by a user for the building lifetime, the operating energy over the life cycle was obtained by multiplying the annual operating energy by the number of years of lifetime, assuming that the operating energy is constant during the building life. By adding the embodied energy to the operating energy over the building life, the life-cycle energy was assessed.

As described in previous sections, the equivalent CO_2 emissions are due to the combustions of natural gas and oil, which are used to generate energy for extracting and manufacturing the building materials (embodied energy) and the building energy operation. The equivalent CO_2 emissions were calculated by utilizing the pollutants coefficients and Global Warming Potential (GWP) index over the life cycle of the building. The system user provides the contribution parts of natural gas and oil.

Normalized scores

Due to the difference in units of cost ($), energy (kWh) and equivalent CO_2 emissions (kg), the normalized scale (Tang *et al.* 1984), from 0 to 1, was used for the life-cycle energy (N_{kWh}); life-cycle cost ($N_{\$}$); and equivalent CO_2 emissions (N_{co_2}). For instance, the normalized scale for the life-cycle cost ($N_{\$}$) is determined by:

$$N_{\$} = (C_a - C_{min}) / (C_{max} - C_{min}) \quad (6.2)$$

where:

$N_{\$}$ = normalized value for the life-cycle cost of alternative *a*;

C_a = the value of life-cycle cost for alternative *a* [$];

C_{min} = the minimum value of the life-cycle cost with respect to all alternatives [$]; and

C_{max} = the maximum value of the life-cycle cost with respect to all alternatives [$].

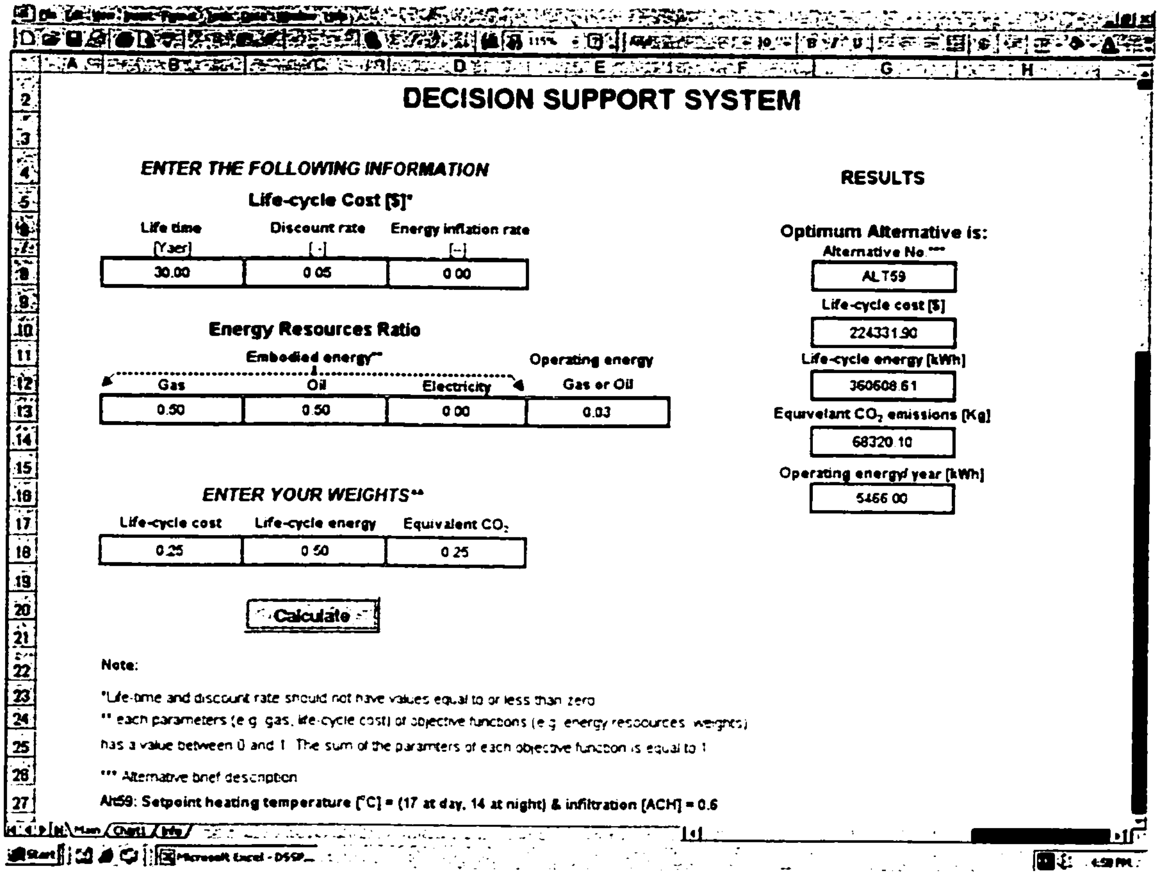
Similarly, normalized scales for the life-cycle energy and equivalent CO_2 emissions were established. Then the normalized score for each alternative is determined by using the following formula (6.3):

$$\text{Normalized score} = W_1 (N_{\$}) + W_2 (N_{kWh}) + W_3 (N_{co_2}) \quad (6.3)$$

where:

W_1, W_2 and W_3 = weighting factors used for evaluating the overall impact of design alternatives. The weighting factors represent the importance given by the user to each of three criteria: life-cycle energy, life-cycle cost, and equivalent CO_2 emissions.

Figure 6.2 presents the interface menu for the decision support system including example of the input data, which can be inserted by the system users.



DECISION SUPPORT SYSTEM

ENTER THE FOLLOWING INFORMATION

Life-cycle Cost [$]*

Life time [Yaer]	Discount rate [-]	Energy inflation rate [-]
30.00	0.05	0.00

Energy Resources Ratio

Embodied energy** Gas	Oil	Electricity	Operating energy Gas or Oil
0.50	0.50	0.00	0.03

*ENTER YOUR WEIGHTS***

Life-cycle cost	Life-cycle energy	Equivalent CO_2
0.25	0.50	0.25

RESULTS

Optimum Alternative is:

Alternative No.***: ALT59

Life-cycle cost [$]: 224331.90

Life-cycle energy [kWh]: 360608.61

Equivelant CO_2 emissions [Kg]: 68320.10

Operating energy/ year [kWh]: 5466.00

Note:

*Life-time and discount rate should not have values equal to or less than zero

** each parameters (e.g. gas, life-cycle cost) of objective functions (e.g. energy resources, weights) has a value between 0 and 1. The sum of the paramters of each objective function is equal to 1

*** Alternative brief description

Alt59: Setpoint heating temperature [°C] = (17 at day, 14 at night) & infiltration [ACH] = 0.6

Figure 6.2. Interface section of the decision support system

Sensitivity analysis of the DSS

Several applications were performed by the DSS to analyze the sensitivity of the system corresponding to different parameters and their relevant impact. The following input data (Figure 6.2) were used: (i) the life of the house is 30 years, (ii) the interest rate including inflation is 5%, and (iii) the energy escalation rate is 0%. In Quebec the hydro-electricity accounts for about 97% of electricity used in the residential sector. It is generally assumed that the generation of hydro-electricity does not produce greenhouse gases. For the equivalent CO_2 emissions, it was assumed that 3% of heating consumption was from heating oil and natural gas.

The remaining part of heating consumption is produced by hydro-electricity. It was also assumed that the embodied energy came from 50% of natural gas and 50% of oil. In the first analysis, the sensitivity of results, given by the DSS was verified against the following factors, presented in table 6.13.

Table 6.13. Sensitivity analysis of DSS due to the modifications of weighting factors

Weighting factors [%]			Best alternatives for given set of parameters
Life-cycle cost	Life-cycle energy	Equivalent CO_2 emissions	
20	40	40	Alt59
40	30	30	Alt21
group 1 60	20	20	Alt21
80	10	10	Alt21
100	0	0	Alt21
40	20	40	Alt21
30	40	30	Alt59
20	group 2 60	20	Alt59
10	80	10	Alt71
0	100	0	Alt89
40	40	20	Alt59
30	30	40	Alt21
20	20	group 3 60	Alt21
10	10	80	Alt21
0	0	100	Alt8

The following methodology was implemented to perform the sensitivity of the DSS:

The weighting factors for the life-cycle cost were modified at the beginning by using weighting factor of 20%, then a graduate increasing value of 20% was applied (group 1, Table 6.13) whereas the total of the weighting factors used for the life-cycle cost, life-cycle energy and equivalent CO_2 emissions is equal to 100%. Similarly, the weighting factors for life-cycle energy and equivalent CO_2 emissions were applied.

It was noticed that the sensitivity of the DSS due to the change of life-cycle cost is less than that for life-cycle energy and equivalent CO_2 emissions. This is due to that many of the alternatives are not cost-effective today because the present house is already energy-efficient, and the electricity cost charged by the utility company is relatively low. Table 6.14 illustrates the description of the alternatives presented in table 6.13.

Table 6.14. Description of the design alternatives that performed in table 6.13

Design alternatives	Abbreviation
Thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$]: 2.2, 3.4 and 5.3	Alt8
Thermal mass walls for the internal above ground walls is 50% of that of the base case house	Alt21
Combination between Set point heating temperature [^oC] and Airtightness [ach]: (17 at day, 14 at night) and (0.6)	Alt59
Combination between thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Setpoint heating temperature [^oC] and Airtightness [ach]: (8.8, 10.57, 17.61) and (17 at day, 14 at night) and (0.6)	Alt71
Combination between thermal resistance of exterior walls and roof [$m^2 \cdot {}^oC/W$] and Thermal resistance of windows [$m^2 \cdot {}^oC/W$] and Glazing-to-wall ratio [%] and Setpoint heating temperature [^oC] and Airtightness [ach]: (8.8, 10.57, 17.61) and (0.88) and (N=0, E=1, W=2, S=60) and (17 at day, 14 at night) and (0.6)	Alt89

Furthermore, the sensitivity of the selected design alternatives, included in the DSS was graphically examined for the weighting factors to show the shape of variation for the overall alternatives. Figures 6.3 to 6.5 illustrate the sensitivity of the DSS due to modification of the weighting factors of the life-cycle cost, life-cycle energy and equivalent CO_2 emissions. The description of the overall alternatives used for the database section of the DSS is presented in previous sections from tables 6.4 to 6.12.

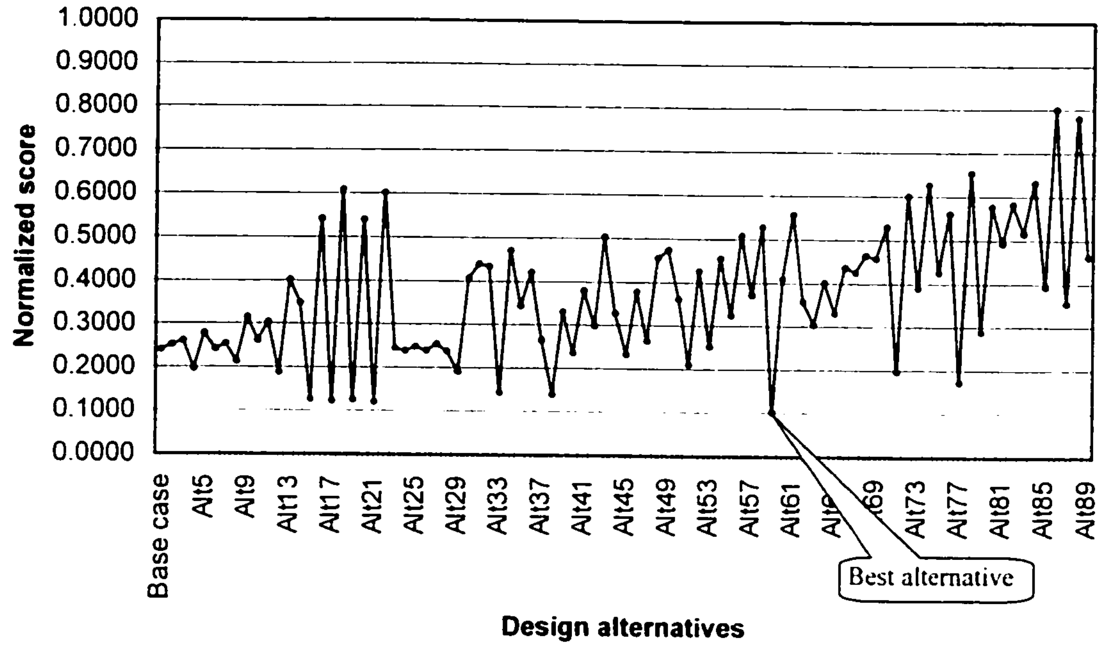


Figure 6.3. Sensitivity due to the use of weights: 50% for the life-cycle cost, 50% for the life-cycle energy, and 0% for the equivalent CO_2 emissions

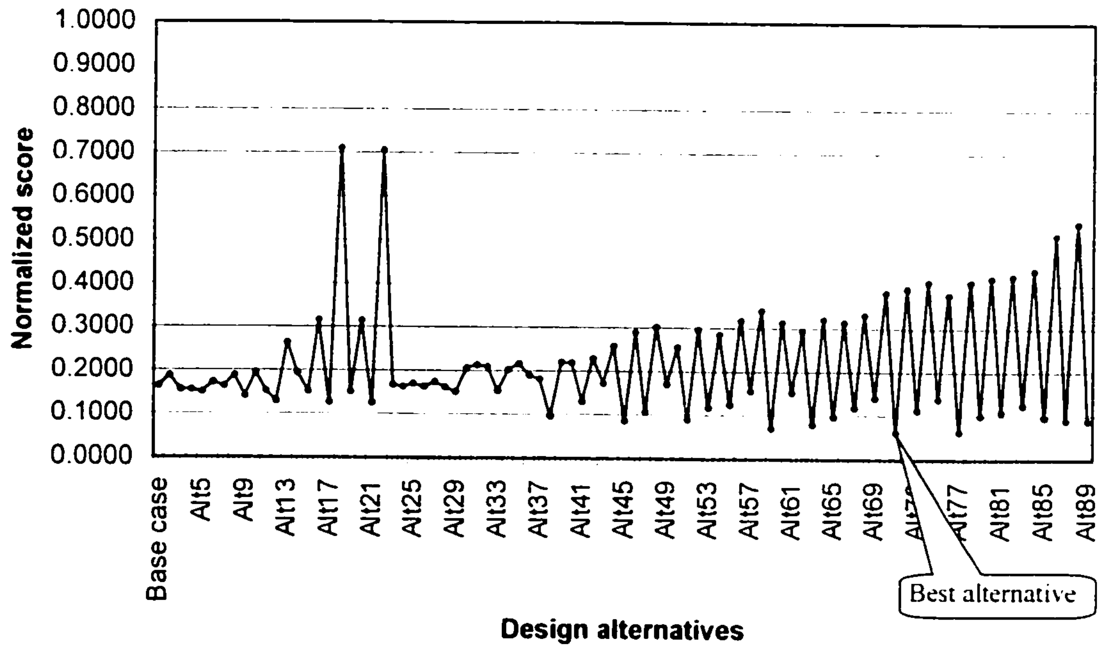


Figure 6.4. Sensitivity due to the use of weights: 0% for the life-cycle cost, 50% for the life-cycle energy and 50% for the equivalent CO_2 emissions

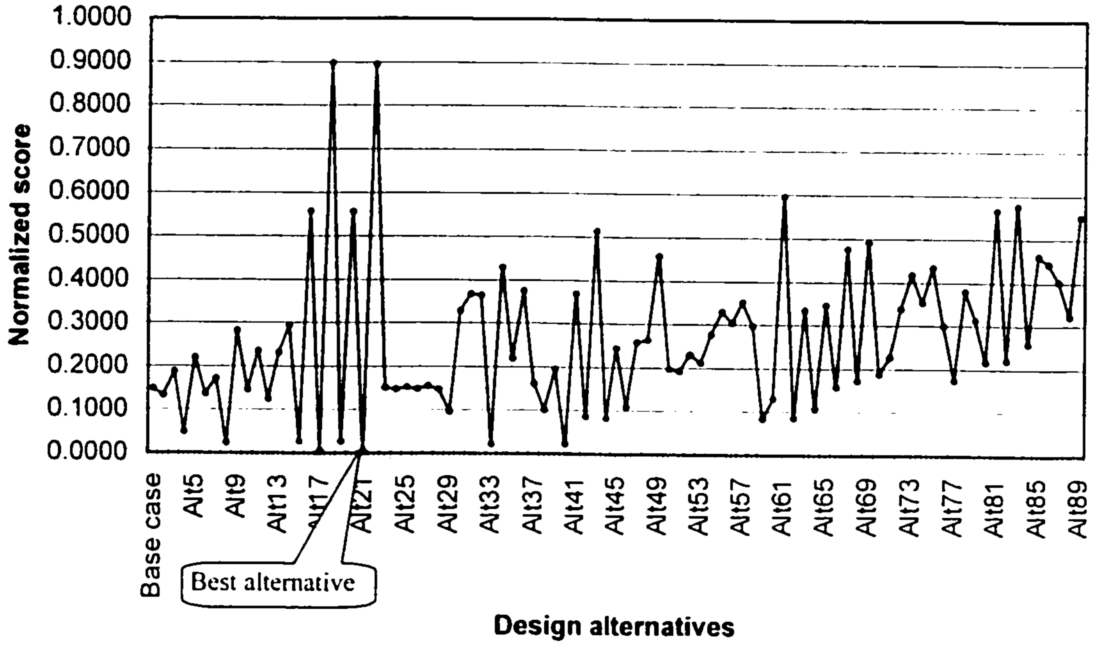


Figure 6.5. Sensitivity due to the use of weights: 50% for the life-cycle cost, 0% for the life-cycle energy; and 50% for the equivalent CO_2 emissions

From the sensitivity analysis, it is clearly demonstrated that the DSS is sensitive to the change of the weighting factors for the life-cycle analysis of the house. This behavior is a strong indication of the tool performance efficiency. For instance, the best estimated alternatives were Alt59 (Figure 6.3), Alt71 (Figure 6.4) and Alt21 (Figure 6.5), when different weighting factors were used. Moreover, the shape of variation for the normalized scores of the selected design alternatives was modified, when the weighting factors were changed. The sensitivity due to the change of other parameters such as the lifetime of the building and interest rate are shown in Appendix B, whereas the equal weighting factors are used then.

The Decision Support System (DSS) is built to provide the essential data required for the energy-efficient design of low-residential buildings for architects and building designers. Different applications can be envisaged: (i) using the DSS interface section as a quick tool to find out the best design alternative based on the life-cycle analysis of the base case house, selected design alternatives, and the information provided by users; and (ii) Using the information of the minimum and maximum values of the selected design alternatives gives building designers a range of values, which can be used to improve the energy-efficient design. For instance, the minimum and maximum values the design alternatives for the basement thermal resistance are 2.2 and 8.8 $m^2 \cdot {}^oC/W$, respectively (Table 6.4). The performance of these alternatives have been evaluated corresponding to the life-cycle analysis; Thus, using these information obtained in the DSS, enables a designer to select the suitable alternative for his design.

From the previous discussion, the Decision Support System is an effective tool, which can be used by building designers to improve their energy-efficient design especially during the preliminary design stage, as it provides many design alternatives and concepts for the energy-efficient design.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The literature search indicates two approaches for the energy-efficient design: (i) the engineering approach, and (ii) the architectural approach. The first approach was used by building engineers to improve the thermal performance of buildings, while the second approach, used by architects aimed to develop the energy-efficiency of buildings based on experience and the rules of thumb. A step forward to develop the techniques and tools used by researchers in both approaches was required to investigate the potential of these tools and their impact on the energy performance of buildings.

The objective of this study is to develop a methodology to improve the energy performance and provide support for the energy-efficient design of low-residential buildings in Canada. This research presents the optimum solutions and recommendations for the design of energy-efficient house in Montreal, Canada to be considered in the future by architects and engineers. Several design alternatives have been developed using both parametric and non-parametric approaches. The performance of design alternatives has been evaluated by using the multi-attribute life-cycle analysis including: (i) life cycle energy; (ii) life-cycle cost, and (iii) environmental impact calculated in terms of equivalent CO_2 emissions. A decision support system based on the evaluation of the selected design alternatives has been developed.

7.1 Conclusions and recommendations

The conclusions and recommendations for this research are summarized as follows:

- Although the base case house is already an energy-efficient house, results revealed that there is still potential to improve the thermal performance and to reduce the energy consumption of the house. The methodology used to develop the design alternatives for this house can be applied to other residential buildings to improve their energy-efficient design.

- The integration between the engineering and architectural approaches has been established in this research through: (i) developing several design alternatives for energy-efficient design based on the information-extracted from both approaches, and (ii) evaluating the impact of architectural design on the energy efficiency based on scientific basics, e.g. experiments and theoretical assessments.

- The simulation results indicated that the most selected design alternatives have a considerable impact on the energy consumption of the base case house including the modifications of: (i) the characteristics of the materials of building envelope, (ii) the architectural design and (iii) the house operating conditions. Five parameters having the significant impact on the energy efficiency are investigated: the thermal resistance of building envelope; thermal properties of windows; glazing-to-wall ratio; setpoint heating temperature and the airtightness. Quantifying the impact of such parameters on the energy performance of the base case has been implemented in this study.

- Combination between design alternatives revealed a significant impact on the energy performance of the house. For instance, reducing the air infiltration rate of the house to the level of 0.6 ach at 50 Pa led to a reduction of heating consumption of 17.7% with respect to that of the base case, while using triple-glazed windows having a thermal resistance of 0.88 $m^2.^oC/W$ led to a reduction of 10.5%. The combination between both alternatives revealed a reduction of 28% for the heating consumption. This indicates the impact of the overall design parameters on the energy performance.

- The simulation results also indicated that some of the selected alternatives are not cost-effective today, because the present house is already energy-efficient, and the electricity cost charged by the utility company is relatively low. However, on the medium or long term some of these design alternatives might become more attractive, if energy cost increases, or the tax credits for CO_2 emissions are implemented in Canada.

- A Decision Support System (DSS) for energy-efficient design was developed in this study to support the decision making for building designers. Different applications can be applied: (i) using the DSS interface section as a quick tool to find out the best design alternative based on the life-cycle analysis of the base case house, selected design alternatives, and the information provided by users; and (ii) using the information of the life-cycle analysis for the minimum and maximum values of the selected design alternatives gives building designers a range of values, which enable them to improve the energy-efficient design of new houses.

7.2 Recommendations for the future work

- Improving the performance of the Decision Support System (DSS) by adding additional case studies and providing further recommendations for energy-efficient design. In addition, the integration between the database file of the DSS and computer simulation programs is required to automatically optimize the impact of design modifications on the energy performance of a building.

- Expanding the DSS to make it possible for a user to add his own evaluation for the design parameters in the database of the system. The comparison between the prototype design alternatives contained in the DSS and the user's alternatives will enable him to select the best alternatives.

- Although many design parameters are evaluated in this research, other aspects are expected to have a considerable effect on the energy-efficient design of a building such as the integration between the mechanical and ventilation systems and building design. More efforts are required to evaluate the impact of the entire building systems on the energy-efficient design.

- This research focused on examining the impact of the base case design parameters on the heating consumption during the winter. Expanding this study to explore the effect of such parameters on the cooling consumption in the summer and the interior air temperature is recommended for the future work.

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APPENDIX A

SAMPLE OF THE INPUT FILE OF
THE FINAL CALIBRATED COMPUTER MODEL

```
BEGIN INPUT;

RUN CONTROL:

NEW ZONES.
UNITS (IN=METRIC. OUT=METRIC).
REPORTS (ZONE LOADS);

TEMPORARY LOCATION:
MONTREAL= (LAT=45. LONG=73. TZ=5):
END:

TEMPORARY MATERIALS:
CONCRETE= (L=0.25. K=0.79. CP=0.9. D=1600. ABS=0.75. TABS=0.9. MEDIUM
ROUGH):
BRICK= (L=0.09. K=1.12. CP=0.79. D=2080. ABS=0.75. TABS=0.9. ROUGH):
WALLAIRCEL= (R=0.208. AIR):
PARTAIRCEL= (R=0.18. AIR):
FLORAIR= (R=0.19. AIR):

BASEWALL= (L=0.16. K=0.04. CP=1.38. D=45. ABS=0.75. TABS=0.9. ROUGH):
GRWALLN= (L=0.19. K=0.04. CP=1.38. D=45. ABS=0.75. TABS=0.9. ROUGH):
GRWALLS= (L=0.192. K=0.04. CP=1.38. D=45. ABS=0.75, TABS=0.9. ROUGH):
GRWALLEW= (L=0.193. K=0.04. CP=1.38, D=45. ABS=0.75. TABS=0.9. ROUGH):
FRSTWALLNS= (L=0.192, K=0.04. CP=1.38. D=45. ABS=0.75. TABS=0.9. ROUGH):
FRSTWALLEW= (L=0.193. K=0.04, CP=1.38, D=45, ABS=0.75. TABS=0.9.
ROUGH);
TRIANGLROF= (L=0.37, K=0.04. CP=1.38, D=45. ABS=0.75, TABS=0.9. ROUGH):

STAIRWOOD= (L=0.04, K=0.16, CP=1.63, D=700. ABS=0.75. TABS=0.9. MEDIUM
SMOOTH);
ROOFINSUL= (L=0.424. K=0.04. CP=1.38. D=45. ABS=0.75, TABS=0.9, ROUGH);
SHEATING= (L=0.0125, K=0.054, CP=1.30, D=290. ABS=0.75. TABS=0.9, ROUGH);
GYPBOARD= (L=0.013, K=0.16, CP=1.09. D=800, ABS=0.75. TABS=0.9. SMOOTH):
CARPET= (L=0.015, K=0.043, CP=0.71, D=800, ABS=0.75, TABS=0.9, MEDIUM
ROUGH);
```

FLORWOOD= (L=0.015, K=0.13, CP=1.38, D=600,ABS=0.75, TABS=0.9, MEDIUM SMOOTH);
CELLULOSE= (L=0.1, K=0.04, CP=1.38, D=45, ABS=0.75, TABS=0.9, ROUGH);
CONDECK= (L=0.15, K=0.9, CP=0.9, D=1600, ABS=0.75, TABS=0.9, MEDIUM ROUGH);
BASEINSUL= (L=0.051, K=0.029, CP=1.21, D=40, ABS=0.75, TABS=0.9, ROUGH);
BASECON= (L=0.08, K=0.79, CP=0.9, D=1600, ABS=0.75, TABS=0.9, MEDIUM ROUGH);
CERAMICS= (L=0.02, K=2.0, CP=0.8, D=590, ABS=0.75, TABS=0.9, SMOOTH);
METAL= (R=0.00000347, SMOOTH);
DORINSUL= (L=0.038, K=0.025, CP=1.59, D=24, ABS=0.75, TABS=0.9, ROUGH);
CASEWIN= (R=0.59, SC=0.82, VERY SMOOTH);
FIXWIN= (R=0.56, SC=0.82, VERY SMOOTH);
ASPHALTE= (L=0.005, K=0.065, CP=1.26, D=1100, ABS=0.75, TABS=0.9, MEDIUM ROUGH);
PLYWOD= (L=0.0125, K=0.11, CP=1.21, D=540, ABS=0.75, TABS=0.9, MEDIUM SMOOTH);
WATRPROF= (R=0.15, ROUGH);

END;

TEMPORARY WALLS:
BWAL= (CONCRETE, BASEWALL, GYPBOARD);
GWALN= (BRICK, WALLAIRCEL, SHEATING, GRWALLN, GYPBOARD);
GWALS= (BRICK, WALLAIRCEL, SHEATING, GRWALLS, GYPBOARD);
GWALEW= (BRICK, WALLAIRCEL, SHEATING, GRWALLEW, GYPBOARD);
FWALNS= (BRICK, WALLAIRCEL, SHEATING, FRSTWALLNS, GYPBOARD);
FWALEW= (BRICK, WALLAIRCEL, SHEATING, FRSTWALLEW, GYPBOARD);
PARTIT= (GYPBOARD, PARTAIRCEL, GYPBOARD);
PARTAIR= (PARTAIRCEL);
END;

TEMPORARY FLOORS:
BFLOR= (CONDECK, BASEINSUL, BASECON, CERAMICS);
GFLOR= (GYPBOARD, FLORAIR, FLORWOOD, CARPET);
FFLOR= (GYPBOARD, GYPBOARD, SHEATING, CELLULOSE, FLORAIR, FLORWOOD, CARPET);
ATTICFLOR= (GYPBOARD, SHEATING, ROOFINSUL);
STAIRFLOR= (FLORWOOD, SHEATING, CELLULOSE, FLORAIR, STAIRWOOD);
END;

TEMPORARY ROOFS:
BCEIL= (CARPET, FLORWOOD, FLORAIR, GYPBOARD);
GCEIL= (CARPET, FLORWOOD, FLORAIR, CELLULOSE, SHEATING, GYPBOARD, GYPBOARD);
FCEIL= (ROOFINSUL, SHEATING, GYPBOARD);

```
ROOF= (ASPHALTE, WATRPROF, PLYWOD);
BAYROF= (ASPHALTE, WATRPROF, PLYWOD, TRIANGLROF, SHEATING,
GYPBOARD);
STAIRCEIL= (STAIRWOOD, FLORAIR, CELLULOSE, SHEATING, FLORWOOD);
END;

TEMPORARY WINDOWS:
W1= (CASEWIN);
W2= (FIXWIN);
END;

TEMPORARY DOORS:
EXTDOOR= (METAL, DORINSUL, METAL);
END;

TEMPORARY SCHEDULE (SCHD.L):
MONDAY THRU FRIDAY= (0 TO 6-0.0, 6 TO 8-1,
8 TO 18-0.0, 18 TO 23-1.0, 23 TO 24-0.0);
SATURDAY= (0 TO 6-0.0, 6 TO 23-.5,
23 TO 24-0.0);
SUNDAY= (0 TO 6-0.0, 6 TO 23-.5,
23 TO 24-0.0);
HOLIDAY= SUNDAY;

END;

TEMPORARY SCHEDULE (SCHD.R):
MONDAY THRU FRIDAY= (0 TO 8-1, 8 TO 18-0.0,
18 TO 23-0.5, 23 TO 24-1);
SATURDAY= (0 TO 8-1, 8 TO 23-0.25, 23 TO 24-1);
SUNDAY= (0 TO 8-1, 8 TO 23-0.25, 23 TO 24-1);
HOLIDAY= SUNDAY;

END;

TEMPORARY CONTROLS (CONT):
PROFILES:
JOUR= (1 AT 20, 0 AT 22);
NIGHT= (1 AT 17, 0 AT 19);

SCHEDULES:
MONDAY THRU FRIDAY= (0 TO 6-NIGHT, 6 TO 8-JOUR,
8 TO 18-NIGHT, 18 TO 23-JOUR, 23 TO 24-NIGHT);
SATURDAY= (0 TO 6-NIGHT, 6 TO 23-JOUR,
23 TO 24-NIGHT);
SUNDAY=  (0 TO 6-NIGHT, 6 TO 23-JOUR,
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```
23 TO 24-NIGHT);
HOLIDAY= SUNDAY;

END CONTROLS;

PROJECT= "PROTOTYPE";
LOCATION= MONTREAL;
WEATHER TAPE FROM 01 JAN THRU 31 DEC ;
GROUND TEMPERATURES= (7,7,7,7,12,12,12,12,12,12,7,7);

BEGIN BUILDING DESCRIPTION;

BUILDING= "RAY_VISION HOUSE"
NORTH AXIS= 180;
SOLAR DISTRIBUTION= 1;

DETACHED SHADING "NEIBRE": (10.28 BY 6)
STARTING AT (14.5, 10.28, 1.5)
FACING (270)
TILTED (90);

DETACHED SHADING "NEIBRW": (10.28 BY 8.4)
STARTING AT (-6.0, 0.0, 1.50)
FACING (90)
TILTED (90);

DETACHED SHADING "GRESHED": (10.28 BY 3.60)
STARTING AT (8.45, 10.28, 4.73)
FACING (270)
TILTED (0.0);

DETACHED SHADING "GRWSHED": (6.30 BY 1.80)
STARTING AT (0.0, 2.90, 5.80)
FACING (90)
TILTED (0.0);

DETACHED SHADING "FRSSHED": (8.45 BY 0.96)
STARTING AT (8.45, 0.0, 8.40)
FACING (0.0)
TILTED (0.0);

DETACHED SHADING "FRWSHED": (12.20 BY 0.96)
STARTING AT (8.45, 11.24, 8.40)
FACING (270)
TILTED (0.0);
```

```
DETACHED SHADING "FRNSHED": (8.45 BY 0.96)
STARTING AT (0.0, 10.28, 8.40)
FACING (180)
TILTED (0.0);

DETACHED SHADING "FRESHED": (12.20 BY 0.96)
STARTING AT (0.0, -0.96, 8.40)
FACING (90)
TILTED (0.0);

ZONE 1 "BASEROOM":
ORIGIN: (0.0, 0.0, 0.0);
NORTH AXIS= 0.0:

BASEMENT WALLS:

STARTING AT (0.0, 3.77, 0.0)
FACING (270)
TILTED (90)
BWAL (3.77 BY 1.5),
STARTING AT (0.0, 0.0, 0.0)
FACING (180)
TILTED (90)
BWAL (8.45 BY 1.5),
STARTING AT (8.45, 0.0, 0.0)
FACING (90)
TILTED (90)
BWAL (3.77 BY 1.5);

EXTERIOR WALLS:

STARTING AT (0.0, 3.77, 1.50)
FACING (270)
TILTED (90)
BWAL (3.77 BY 1.35),
STARTING AT (0.0, 0.0, 1.5)
FACING (180)
TILTED (90)
BWAL (8.45 BY 1.35)
WITH WINDOWS OF TYPE
W1 (1.52 BY 0.50)
AT (1.18, 0.50)
WITH WINDOWS OF TYPE
W1 (0.92 BY 0.50)
AT (6.50, 0.50),
STARTING AT (8.45, 0.0, 1.50)
```

```
FACING (90)
TILTED (90)
BWAL (3.77 BY 1.35);

INTERZONE PARTITIONS:

STARTING AT (8.45, 3.77, 0.0)
FACING (0.0)
TILTED (90)
PARTIT (8.45 BY 2.55)
ADJACENT TO ZONE (2);

SLAB ON GRADE FLOORS:

STARTING AT (0.0, 3.77, 0.0)
FACING (180)
TILTED (180)
BFLOR (8.45 BY 3.77);

INTERZONE CEILINGS:

STARTING AT (0.0, 0.0, 2.85)
FACING (180)
TILTED (0.0)
BCEIL (8.45 BY 3.77)
ADJACENT TO ZONE (5);

INFILTRATION= 0.00185,
CONSTANT,
FROM 01JAN THRU 31DEC;

PEOPLE= 2,
SCHD.R,
FROM 01 JAN THRU 31 DEC;

CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 JAN THRU 30 APR;
CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 OCT THRU 31 DEC;
END ZONE;
```

```
ZONE 2 "BASESERV":
ORIGIN: (0.0, 3.77, 0.0);
NORTH AXIS= 0.0;

BASEMENT WALLS:

STARTING AT (0.0, 1.73, 0.0)
FACING (270)
TILTED (90)
BWAL (1.73 BY 1.5),
STARTING AT (8.45, 0.0, 0.0)
FACING (90)
TILTED (90)
BWAL (1.73 BY 1.5);

EXTERIOR WALLS:

STARTING AT (0.0, 1.73, 1.50)
FACING (270)
TILTED (90)
BWAL (1.73 BY 1.35),
STARTING AT (8.45, 0.0, 1.50)
FACING (90)
TILTED (90)
BWAL (1.73 BY 1.35);

INTERZONE PARTITIONS:

STARTING AT (8.45, 1.73, 0.0)
FACING (0.0)
TILTED (90)
PARTIT (8.45 BY 2.55)
ADJACENT TO ZONE (3),
STARTING AT (0.0, 0.0, 0.0)
FACING (180)
TILTED (90)
PARTIT (8.45 BY 2.55)
ADJACENT TO ZONE (1);

SLAB ON GRADE FLOORS:

STARTING AT (0.0, 1.73, 0.0)
FACING (180)
TILTED (180)
BFLOR (8.45 BY 1.73);
INTERZONE CEILINGS:
```

```
STARTING AT (0.0, 0.0, 2.85)
FACING (180)
TILTED (0.0)
BCEIL (6.45 BY 1.73)
ADJACENT TO ZONE (6);

INFILTRATION= 0.000262,
CONSTANT,
FROM 01JAN THRU 31DEC;

PEOPLE= 0.0,
SCHD.L,
FROM 01 JAN THRU 31 DEC;

CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 JAN THRU 30 APR;
CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 OCT THRU 31 DEC;

END ZONE;

ZONE 3 "BASEREC":
ORIGIN: (0.0, 5.50, 0.0);
NORTH AXIS= 0.0;

BASEMENT WALLS:

STARTING AT (0.0, 4.78, 0.0)
FACING (270)
TILTED (90)
BWAL (4.78 BY 1.5),
STARTING AT (3.0, 4.78, 0.0)
FACING (0.0)
TILTED (90)
BWAL (3.0 BY 1.5),
```

```
STARTING AT (8.45, 4.78, 0.0)
FACING (0.0)
TILTED (90)
BWAL (2.39 BY 1.5),
STARTING AT (8.45, 0.0, 0.0)
FACING (90)
TILTED (90)
BWAL (4.78 BY 1.5);

EXTERIOR WALLS:

STARTING AT (0.0, 4.78, 1.5)
FACING (270)
TILTED (90)
BWAL (4.78 BY 1.35),
STARTING AT (3.0, 4.78, 1.5)
FACING (0.0)
TILTED (90)
BWAL (3.0 BY 1.35)
WITH WINDOWS OF TYPE
W1 (1.83 BY 0.92)
AT (0.45, 0.10),
STARTING AT (8.45, 4.78, 1.5)
FACING (0.0)
TILTED (90)
BWAL (2.39 BY 1.35),
STARTING AT (8.45, 0.0, 1.5)
FACING (90)
TILTED (90)
BWAL (4.78 BY 1.35)
WITH WINDOWS OF TYPE
W1 (0.92 BY 0.50)
AT (1.12, 0.50);

INTERZONE PARTITIONS:

STARTING AT (0.0, 0.0, 0.0)
FACING (180)
TILTED (90)
PARTIT (8.45 BY 2.55)
ADJACENT TO ZONE (2);
```

```
SLAB ON GRADE FLOORS:

STARTING AT (0.0, 4.78, 0.0)
FACING (180)
TILTED (180)
BFLOR (8.45 BY 4.78);

INTERZONE CEILINGS:

STARTING AT (0.0, 0.0, 2.85)
FACING (180)
TILTED (0.0)
BCEIL (4.23 BY 1.22)
ADJACENT TO ZONE (7),
STARTING AT (4.23, 0.0, 2.85)
FACING (180)
TILTED (0.0)
BCEIL (4.22 BY 1.22)
ADJACENT TO ZONE (8),
STARTING AT (0.0, 1.22, 2.85)
FACING (180)
TILTED (0.0)
BCEIL (8.45 BY 3.56)
ADJACENT TO ZONE (9);

INFILTRATION= 0.000724,
CONSTANT,
FROM 01JAN THRU 31DEC;
PEOPLE= 1,
SCHD.L,
FROM 01 JAN THRU 31 DEC;
CROSS MIXING= 0.008, FROM ZONE 4,
FROM 01JAN THRU 31DEC;

CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 JAN THRU 30 APR;
CONTROLS= CONT,
2.0 HEATING,
0 COOLING,
50 PERCENT MRT,
FROM 01 OCT THRU 31 DEC;

END ZONE;
```

APPENDIX B

SENSITIVITY ANALYSIS FOR THE DECISION SUPPORT SYSTEM

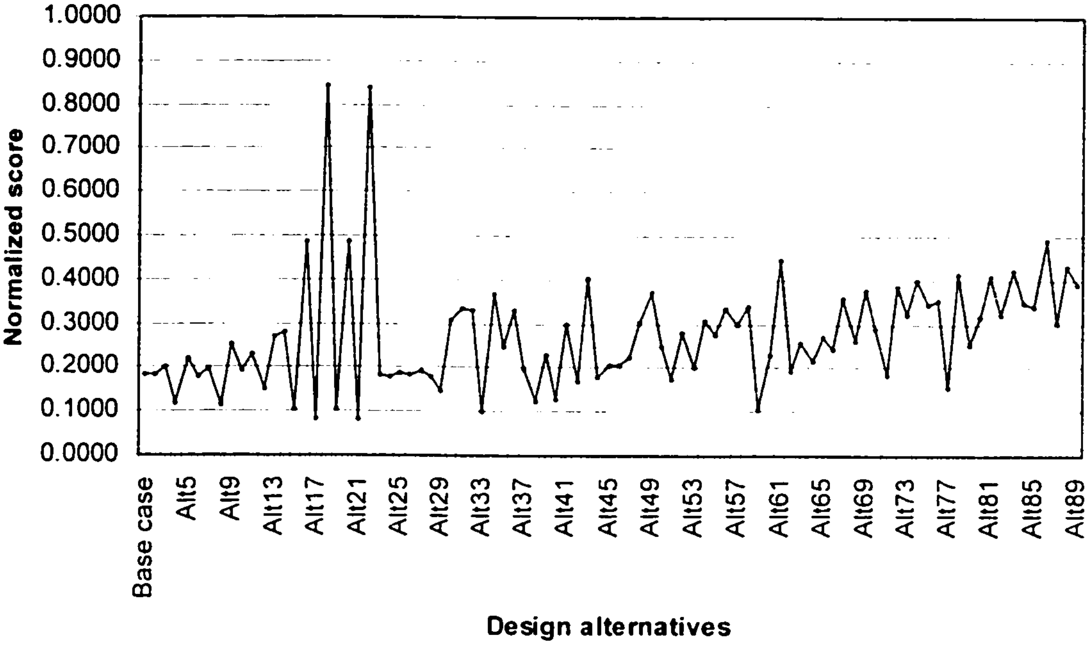

Figure B.1. Sensitivity due to using a lifetime of 10 years

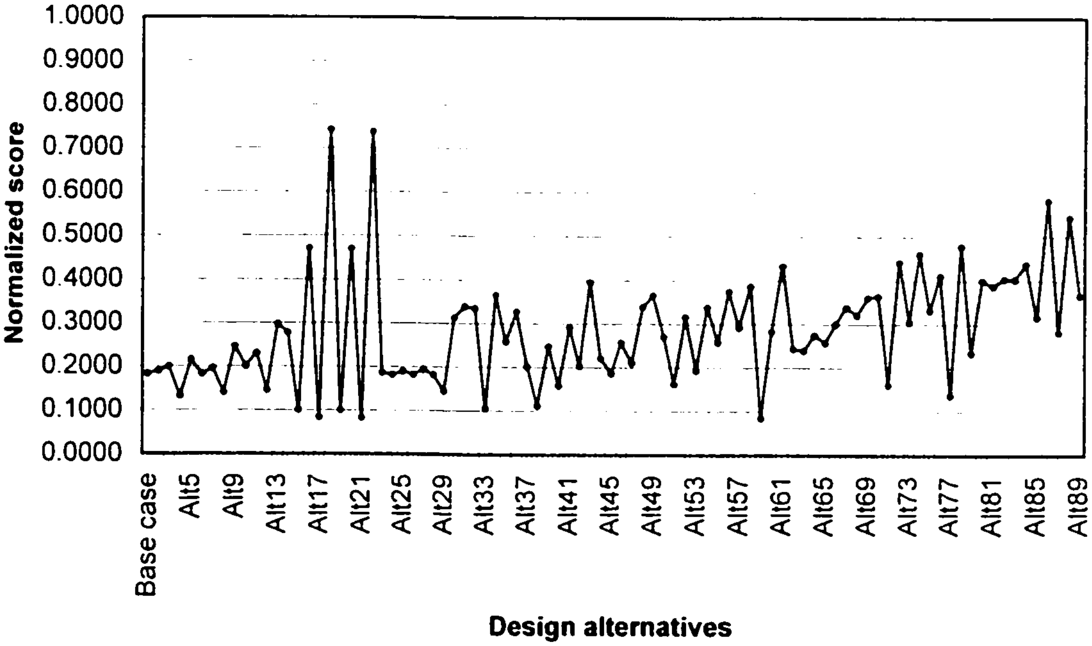

Figure B.2. Sensitivity due to using a lifetime of 30 years

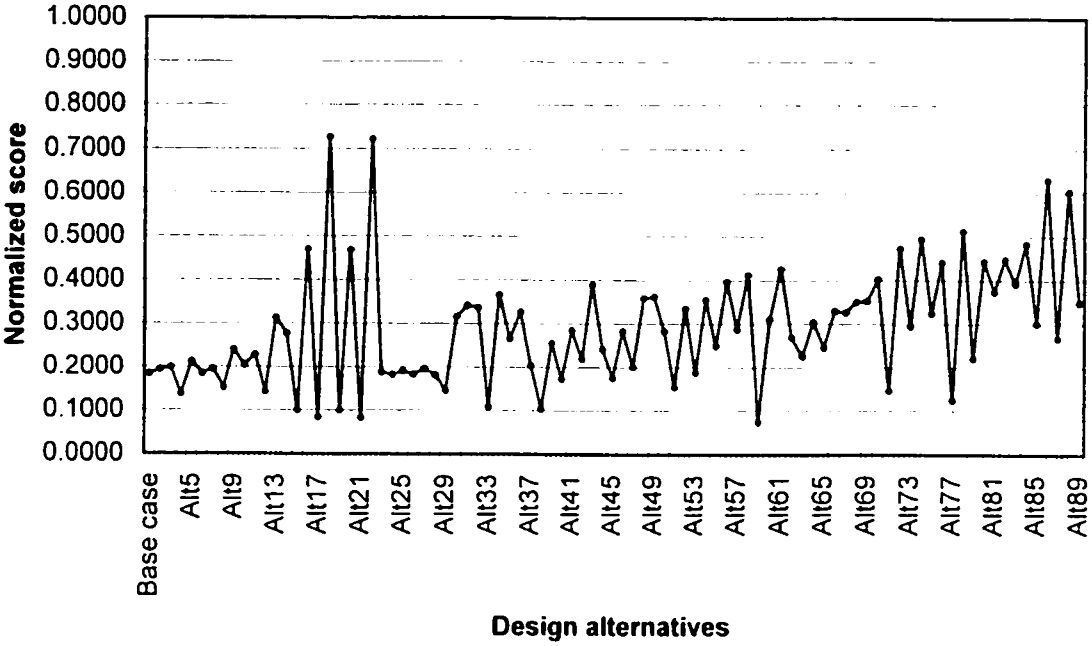

Figure B.3. Sensitivity due to using a lifetime of 50 years

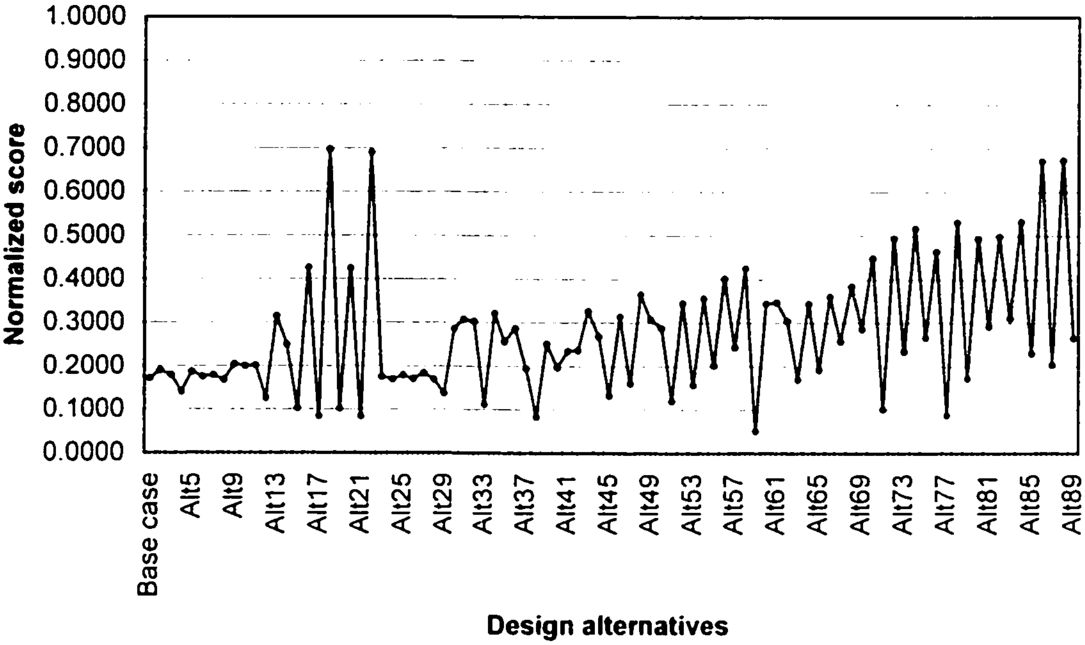

Figure B.4. Sensitivity due to using a discount rate of 0%

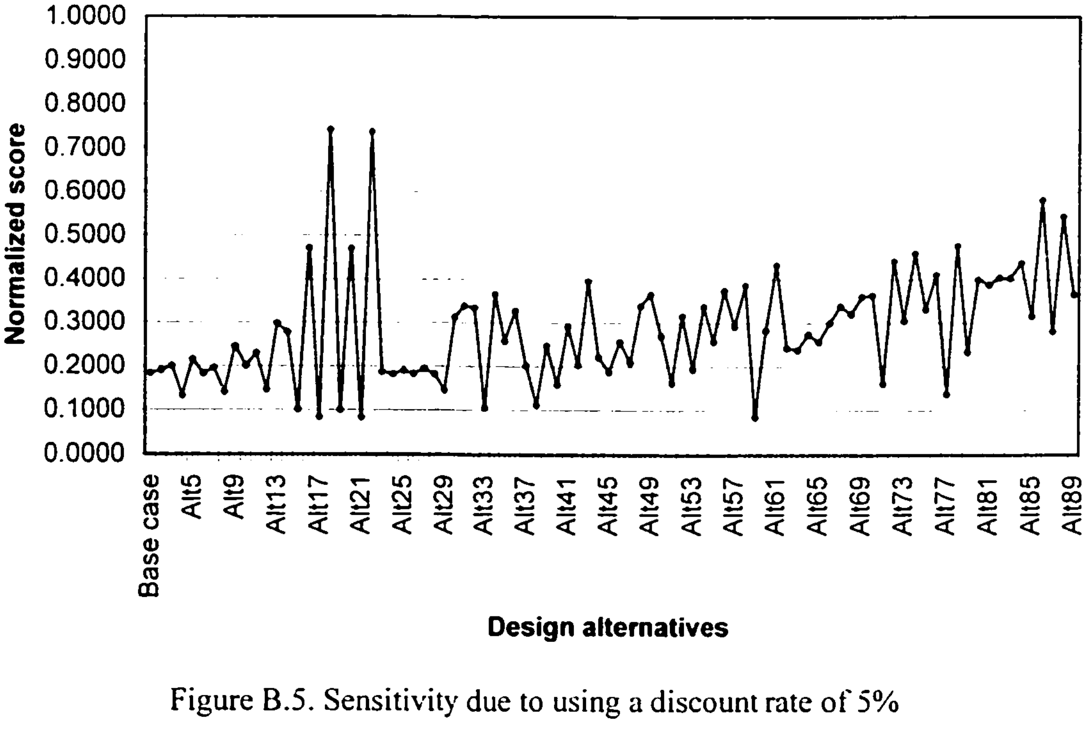

Figure B.5. Sensitivity due to using a discount rate of 5%

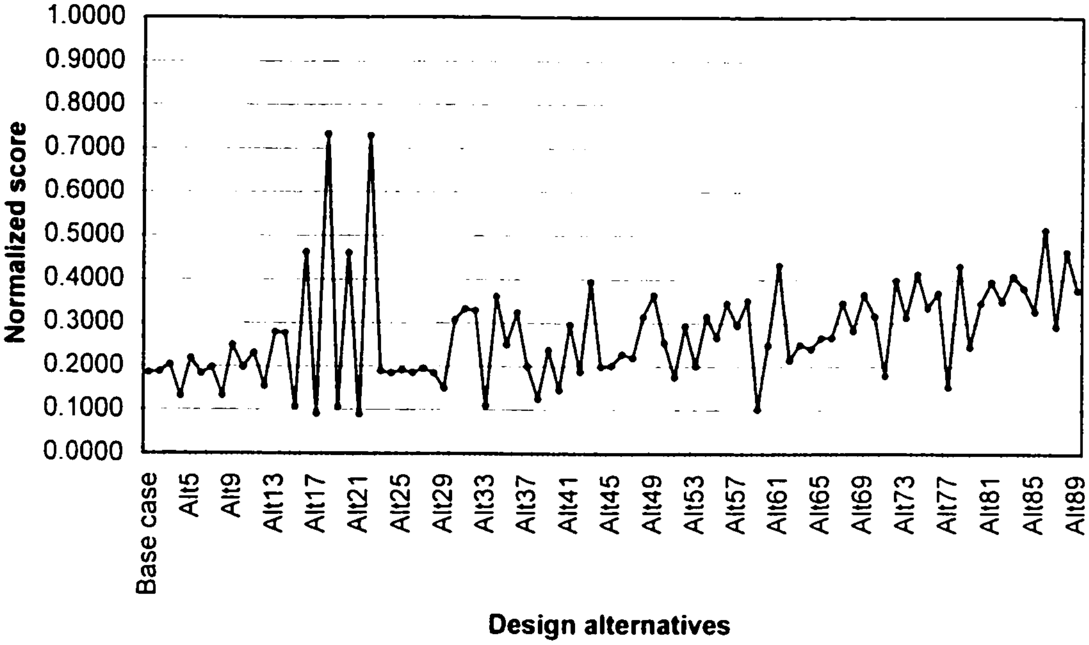

Figure B.6. Sensitivity due to using a discount rate of 10%

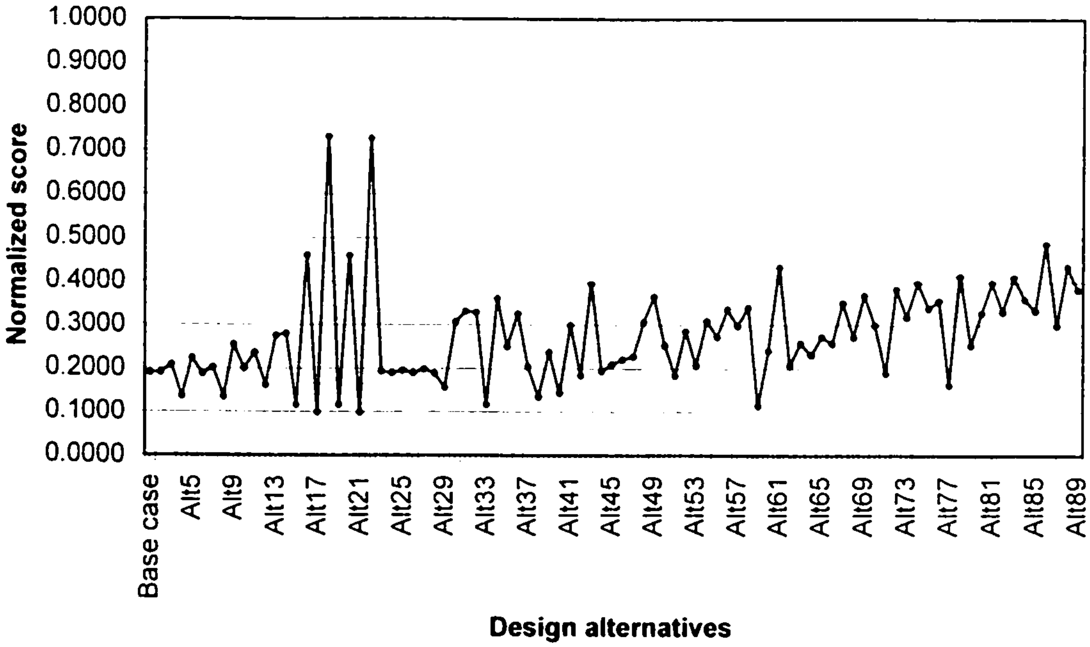

Figure B.7. Sensitivity due to using a discount rate of 15%

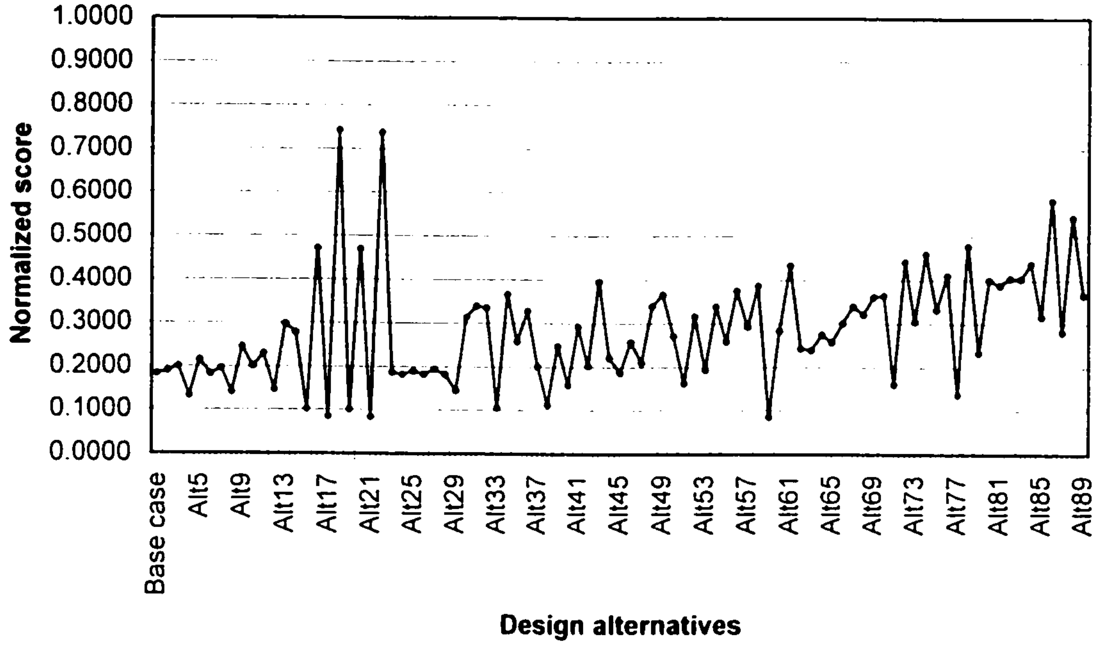

Figure B.8. Sensitivity due to using an energy inflation rate of 0%

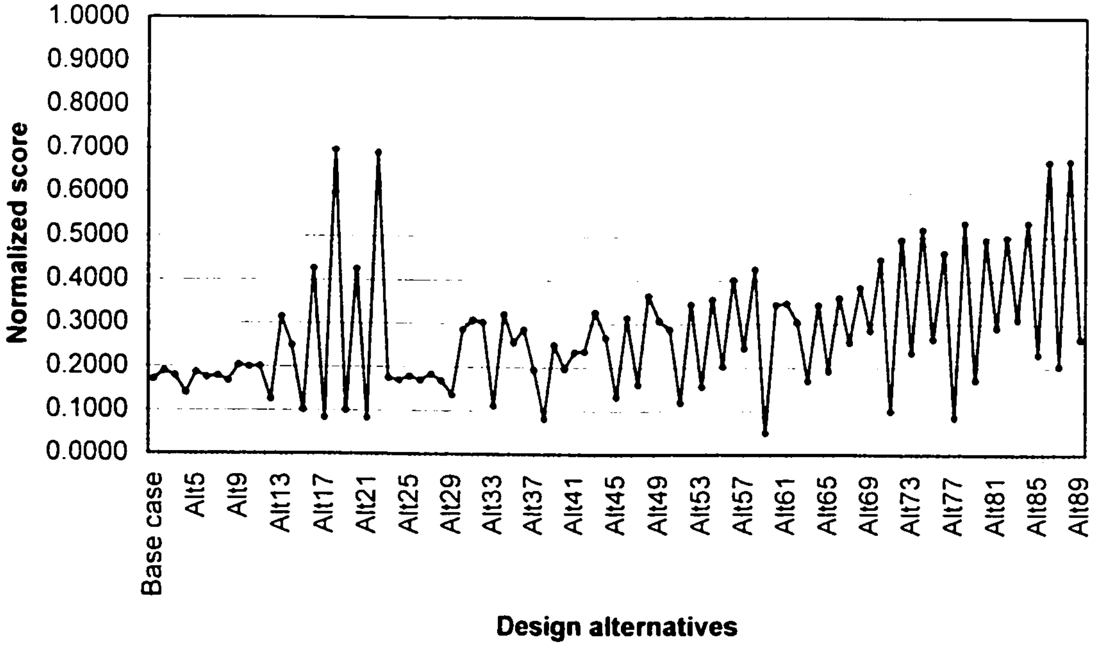

Figure B.9. Sensitivity due to using an energy inflation rate of 5%

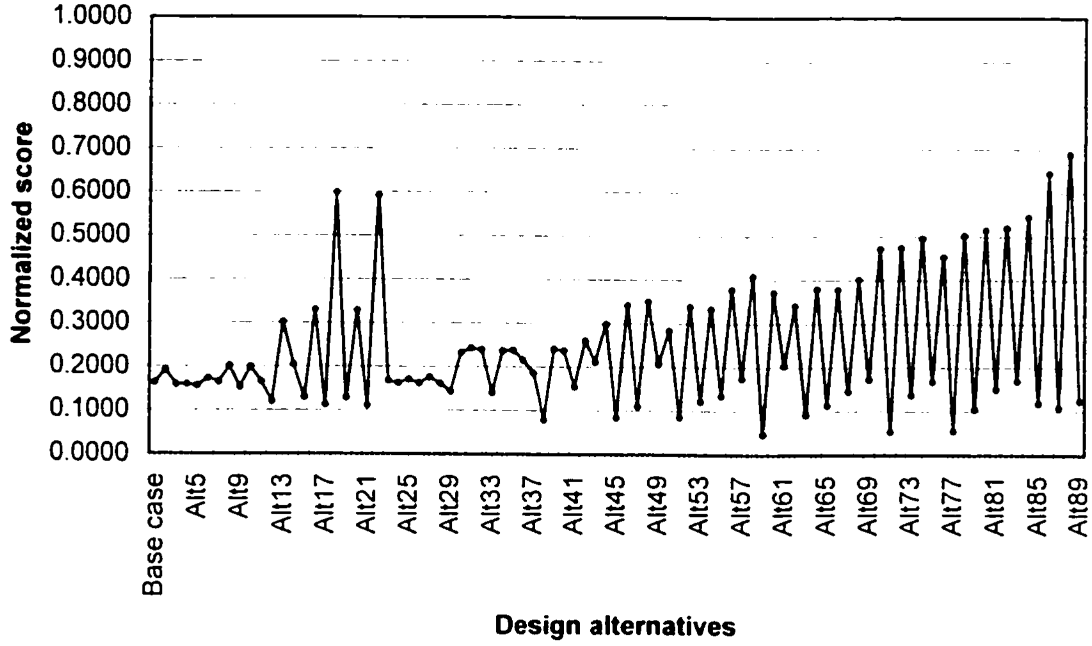

Figure B.10. Sensitivity due to using an energy inflation rate of 10%

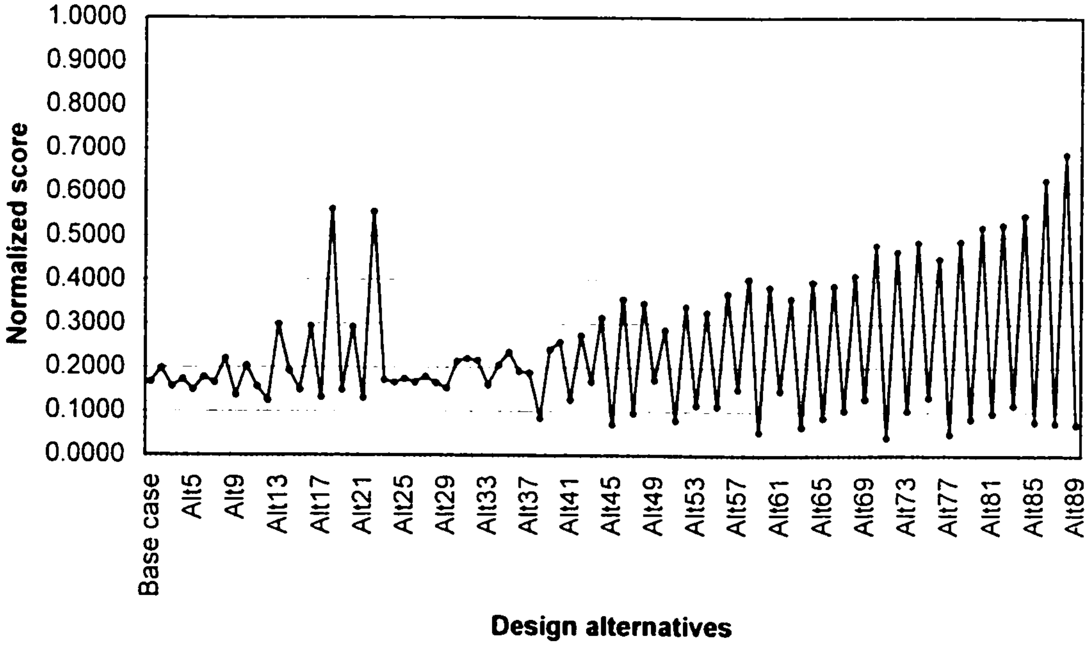

Figure B.11. Sensitivity due to using an energy inflation rate of 15%

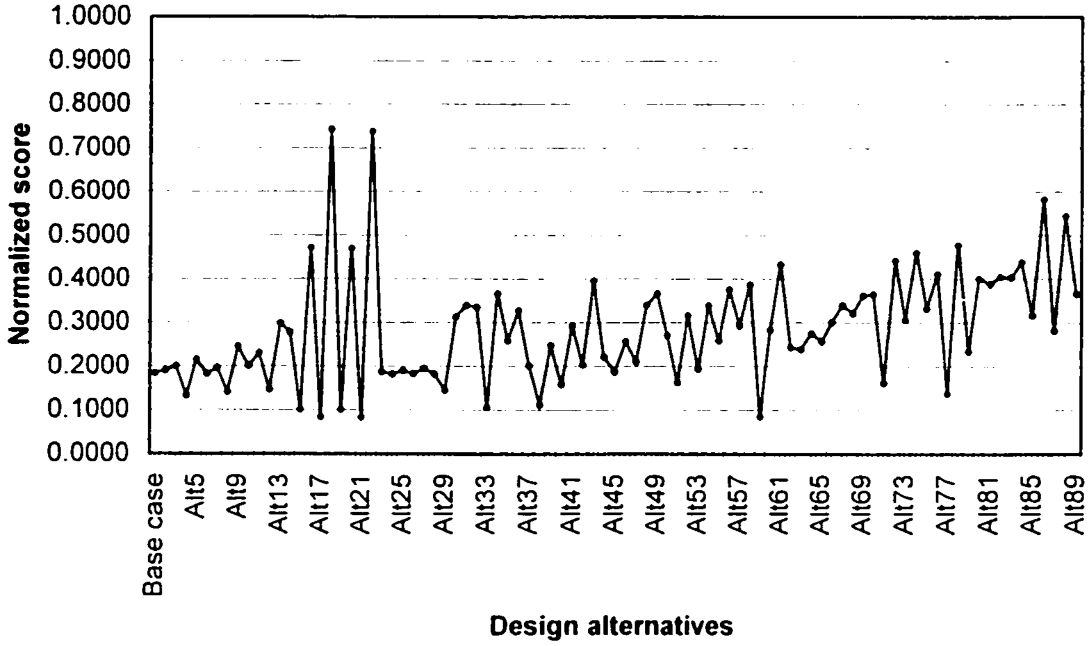

Figure B.12. Sensitivity due to using weight of 3% for the operating energy

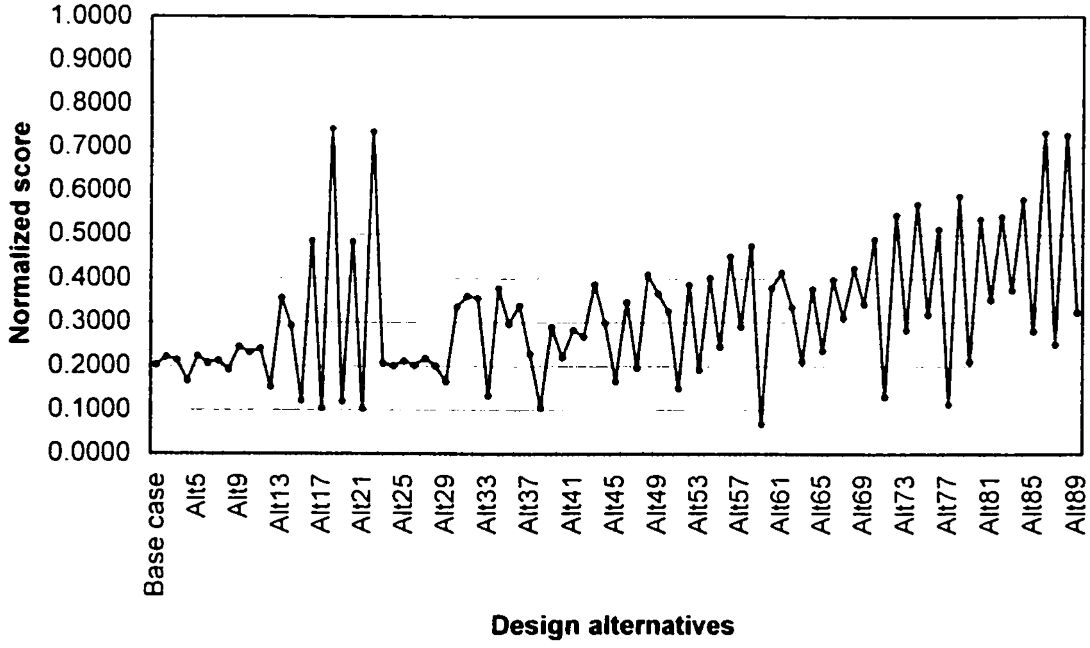

Figure B.13. Sensitivity due to using weight of 20% for the operating energy

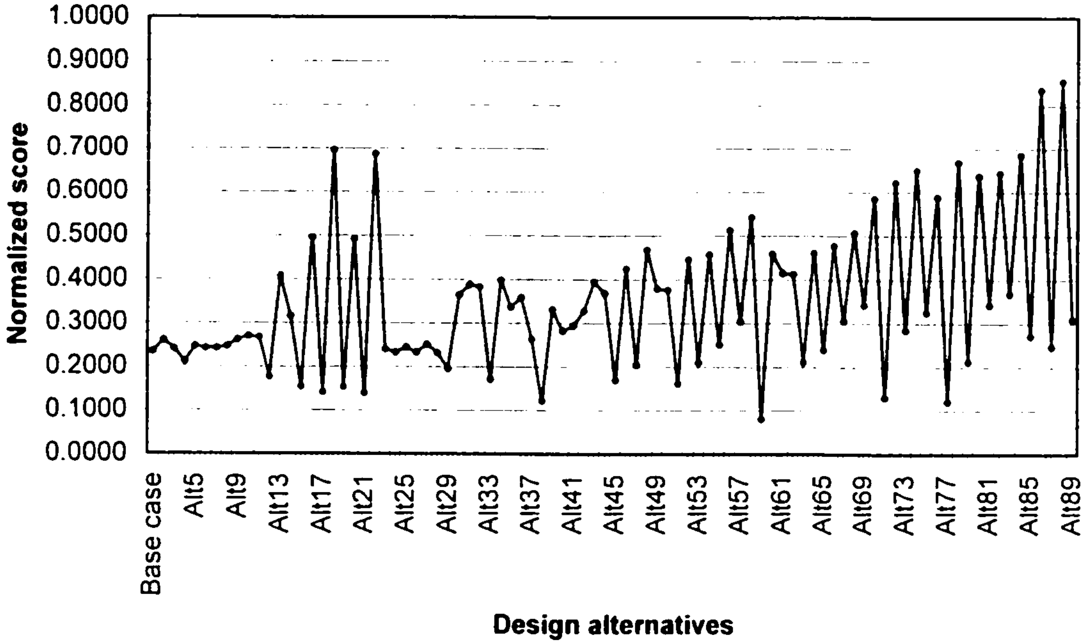

Figure B.14. Sensitivity due to using weight of 40% for the operating energy

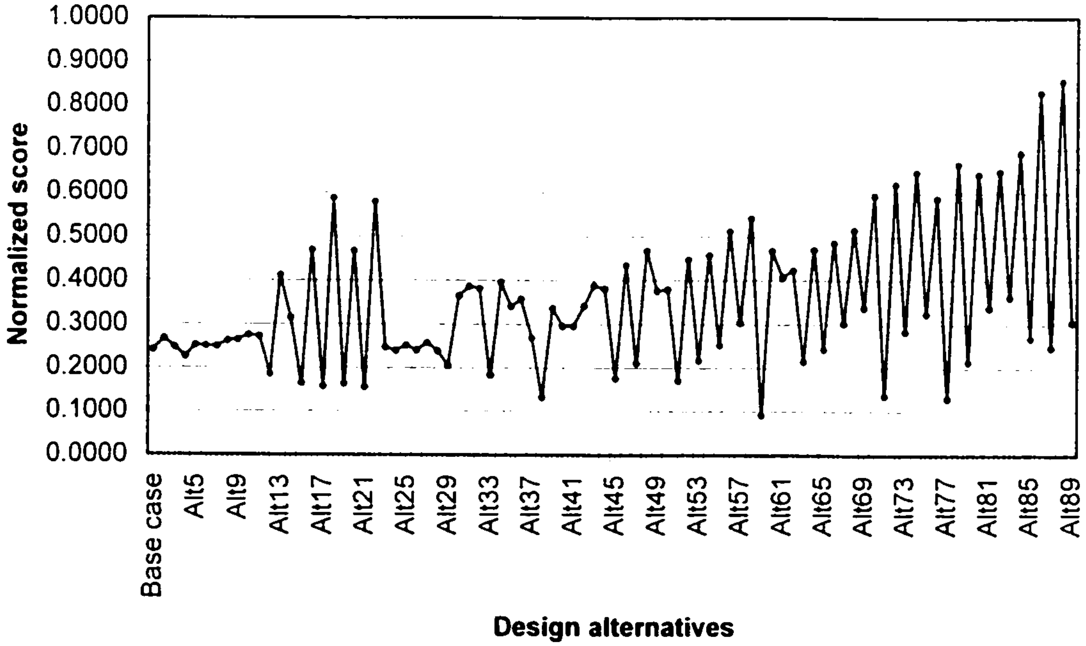

Figure B.15. Sensitivity due to using weight of 80% for the operating energy

APPENDIX C

CONTRIBUTIONS TO RESEARCH AND DEVELOPMENT

Kassab, M., Zmeureanu, R., and Derome, D. 2002. "Multi-Attribute Life-Cycle Analysis of a Sustainable House in Montreal". Accepted for the World Renewable Energy Congress (WREC), Cologne, Germany, Vol. VII, July 2002.

Kassab, M., Derome, D., and Zmeureanu, R. 2002. "Searching for the Improvement of an Energy-Efficient House in Montreal". Accepted for the Sustainable Buildings 2002 Conference, Oslo, Norway, September 2002.