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Least Cost Analysis of Energy Efficiency Upgrades for Ontario Using Trnsys

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By

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Bachelor of Industrial Engineering

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A project
presented to Ryerson University

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Toronto, Ontario, Canada, 2012

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Abstract

This report presents the methodology for determining least cost energy efficient upgrade solutions in new residential housing using brute force sequential search (BFSS) method for integration into the reference house to reduce energy consumption while minimizing the net present value (NPV) of life cycle costs.

The results showed that, based on the life cycle cost analysis of 30 years, the optimal upgrades resulted in the average of 19.25% (case 1), 31% (case 2a), and 21% (case 2b) reduction in annual energy consumption.

Economic conditions affect the sequencing of the upgrades. In this respect the preferred upgrades to be performed in order are; domestic hot water heating, above grade wall insulation, cooling systems, ceiling insulation, floor insulation, heat recovery ventilator, basement slab insulation and below grade wall insulation.

When the gas commodity pricing becomes high, the more energy efficient upgrades for domestic hot water (DHW) get selected at a cost premium.

Acknowledgments

Over the past eight months I have received help from professors, sponsors, students, friends, and family members which is much appreciated. The help wasn’t only in the form of technical advice, but moral support as well which is just as useful.

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The Canada Mortgage and Housing Corporation (CMHC) for their financial support in this research project, Ms. Aya Dembo, Mr. Tanveer Sayed, Mr. Farhan Khaddad, and Mr. Gurjot Gill for their technical support.

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Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1

1 Introduction

1.1 Overview

Increased environmental awareness and limited energy resources are the driving force behind the escalating importance of the urgent need to reduce energy consumption in the residential sector in Canada. The residential sector is the third largest consumer of end-use energy in Canada (NRCan, 2011). As Figure 1-1 shows the residential sector accounted for approximately 17% of the total energy in Canada.

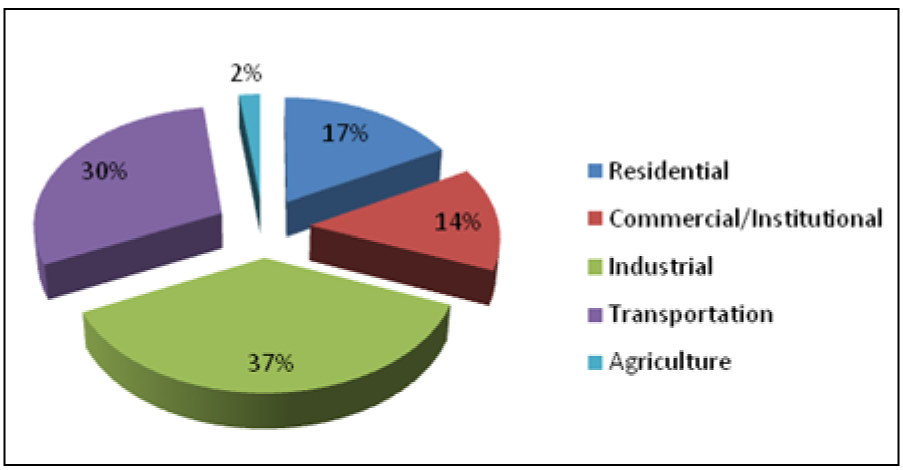

Figure 1-1: Energy use by end-sector, 2007 (NRCan, 2011)

(Dembo, 2011)

In addition, Figure 1-2 shows the fuel types used in Canadian new housing in 2007. As shown in Figure 1-2 Natural gas accounted 42%, electricity 36%, heating oil 8%, wood 4%, dual source 4% and remaining 6% of households' space heating sources. (NRCan, 2010c; 2010d) (Dembo, 2011).

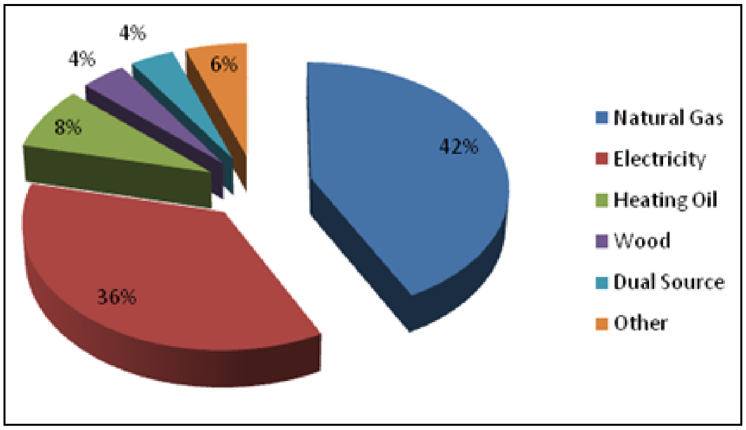

Figure 1-2: Detail percentage of fuel types used in Canadian new housing, 2007 (NRCan, 2010c; NRCan, 2010d; Statistics Canada, 2007) (Dembo, 2011)

Figure 1-3 shows the principal energy sources used in space heating by different provinces in Canada (NRCan, 2010c).

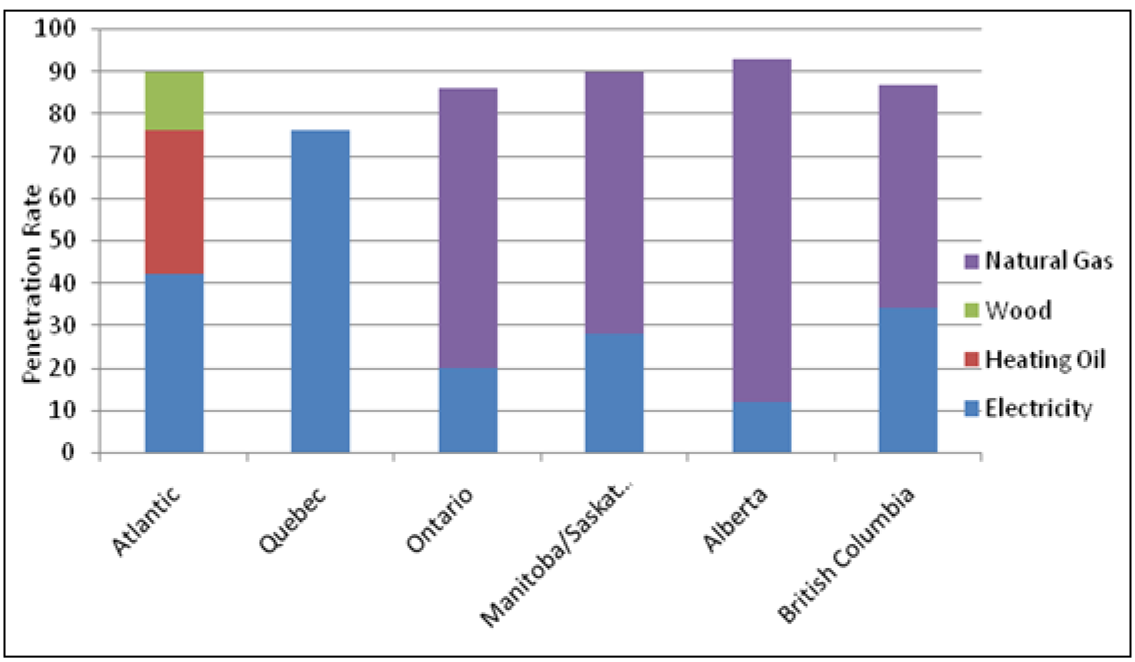

Figure 1-3: Principal energy sources for heating by region, 2007 (NRCan, 2010c) (Dembo, 2011)

As shown in Figure 1-3, most provinces in Canada (Ontario, Manitoba, Saskatchewan, Alberta and British Columbia) use natural gas as the primary fuel for space heating purposes. However, the province of Quebec uses electricity and Atlantic Canada uses electricity and heating oil as the primary fuel to heat the indoor spaces of the home.

In 2004, Ontario accounted for about 30% of Canada's energy consumption (NRCan, 2006). Table 1-1 indicates the electricity demand of all sectors in Ontario. As shown in the Table 1-1 the residential sector consumed 49 TWh in 2010, with an expected increase to 56 TWh by 2020. It was found that the residential sector in 2010 accounted for 32% of electricity demand with a projection for it to remain at 32% by 2020 (NRCan, 2006).

Table 1-1: Electricity Demand in Ontario (TWh)

	1990	2000	2004	2010	2020	2005-2020
Residential	45.3	42.7	45.3	49.2	55.9	1.4
Commercial	40.7	48.6	53.2	62.2	76.2	2.3
Industrial	43.4	44.2	38.0	42.5	45.6	0.5
Transportation	0.6	0.9	0.5	0.8	0.9	1.4
Total	130.0	136.4	136.9	154.8	178.6	1.5

Note: Data taken from Natural Resources Canada (NRCan, 2006)

In addition, in 2007 the average household energy consumption in Canada was approximately 106 GJ (100.5 million Btu) (Statistics Canada, 2007). This high consumption rate has been attributed to the prevalence of a high number of low density single family dwellings and Canada's northerly location (Farahbakhsh, et al., 1997). With this high consumption rate, the residential sector in Canada is facing an urgent need to reduce its primary energy that is being consumed by the existing residential buildings. For instance, the residential sector in Canada has implemented changes to both the national and provincial building codes to amend the ways Canadians have built homes for previous decades. One of the solutions is to develop potential energy efficiency upgrades that can be implemented into the currently practiced housing constructions to achieve significant energy savings. However, the cost of such improvement is one of the greatest barriers. Cost and consumption are two variables that will be influenced economically when energy efficiency measures are added to residential housing upgrades (Farahbakhsh, et al., 1997). These two variables are defined below:

1) Cost: There are costs such as implementation, equipment, and installation, associated with the upgrades leading to higher principal cost or increased mortgage payments.
2) Consumption: The upgrades will reduce the energy consumption of the house leading to lower energy cost.

By coupling these two variables with the interest rate, mortgage period, fuel prices, house characteristics, climate, etc., there could be a decrease in the total annual costs to the homeowner (utilities and mortgage combined). It is the coupling of these two characteristics that deem it necessary to perform life cycle cost analysis (LCCA) (Haines, et al., 2007) to determine the least cost upgrades (LCU) for the promotion of energy conservation opportunities (ECO) (Turner & Doty, 2007) and optimal energy efficiency measure.

Ideally, a set of optimal LCU should be selected based on their overall costs to the homeowner for the desired mortgage period. Then overall energy savings could be determined with a set of the LCU added to the standard housing unit, until the overall cost to the homeowner is the same or less than the standard housing unit without any upgrade.

The outcome of this study is to provide understanding on what upgrades should be incorporated into the new housing sector for improved energy efficiency standards without adding cost to the homeowner over the lifespan of a standard mortgage.

1.2 Objectives of the Research

The objectives of this research are twofold:

1) Develop a method for determining "least cost upgrades" in new residential housing constructions in Ontario.
2) Integrate these energy efficient upgrades into a reference Canadian Centre for housing Technology (CCHT) house that will reduce energy consumption while minimizing the NPV of life cycle costs.

Reduction of end-use energy consumption in the housing sector can be achieved by using a combination of measures such as (Farahbakhsh, et al., 1997):

1) Increasing efficiency
2) Reducing the end-use energy demand
3) Accelerating and increasing the use of renewable energies
4) Adopting new and emerging energy conversion technologies
5) Switching to less carbon-intensive fuels

Canada Mortgage and Housing Corporation (CMHC), a national housing agency, commissioned a study for “Least Cost Housing Upgrades (LCU) for Canadian New Housing” from Ryerson University. One part of this study was to address the new housing construction for different regions and cities in Canada. The objective of this research is to take four cities of Toronto, Ottawa, Thunder Bay and Windsor in Ontario and perform the LCU analysis on a referenced house or residential unit. The reference house that was be used for the basis of this study built by the Canadian Centre for Housing Technology (CCHT) (CCHT, 2011).

1.3 Scope of the Research

The scope of this study is to provide the least cost upgrades for a residential single dwelling home in Ontario (Toronto, Ottawa, Thunder Bay and Windsor) using the following six steps, some of which are iterative:

1) Selection of n prescriptive energy efficient upgrades.
2) Performing a building code analysis.
3) Performing LCCA and energy modeling of prescriptive upgrades.
4) LCU analysis with brute force sequential search algorithm to determine the optimal upgrade sequences.
5) Benchmarking of all prescriptive upgrades and determination of the optimal upgrades.

In order to determine the overall cost of each potential upgrade, ranking of each potential upgrade will be done using a brute force sequential search (BFSS) linear algorithm. Once the lowest NPV of upgrade is determined, it will be applied to the house. This process is repeated until all upgrade categories have been exhausted and an optimal residential unit has been determined.

Chapter 2

2 Literature Review

2.1 Overview

The average household energy consumption in Canada was approximately 106 GJ (100.5 million Btu) (Statistics Canada, 2007). In addition, in 2004, Ontario accounted for about 30% of Canada's energy consumption (NRCan, 2006). The residential sector consumed 49 TWh in 2010, with an expected increase to 56 TWh by 2020. It was found that the residential sector in 2010 accounted for 32% of electricity demand with a projection for it to remain at 32% by 2020 (NRCan, 2006). This high consumption rate has been attributed to the prevalence of a high number of low density single family dwellings and Canada's northerly location ((Farahbakhsh, et al., 1997). With this high consumption rate, the residential sector in Canada is facing an urgent need to reduce its primary energy that is being consumed by the existing residential buildings.

Furthermore, there are numbers of drivers that have a large influence on energy consumption. The following factors need to be considered to understand the nature of these drivers on consumption, but are not limited to:

1) Dwelling characteristics
2) Location
3) Weather
4) Usage patterns
5) Availability of resources
6) Equipment characteristics
7) Code requirements

As a result, for the residential sector in Ontario, energy usage by source can be broken down into six main categories as shown in Table 2-1. In 2003, natural gas at 59% and electricity at 31% were the main contributors to the total energy consumption in Ontario. These two sources accounted for 90% of total energy consumed in Ontario. The Greater Toronto Area (GTA), as the major consumer of energy along with Ottawa, Thunder Bay and Windsor will be considered for this LCU analysis. In this study GTA as the major consumer of energy in Ontario and Canada as shown in Table 2-2 will be used as the reference city for LCU analysis.

Table 2-1: Residential Energy Consumption by Source in Canada (in TJ)

Region	Electricity	Natural Gas	Heating Oil	Wood	Propane	Coal and other	Total
Atlantic provinces	44,800	0	38,300	15,000	2,000	300	100,400
Quebec	183,300	23,600	45,600	54,200	1,100	0	307,800
Ontario	**159,900**	**302,300**	**29,100**	**16,700**	**4,100**	**0**	**512,100**
Manitoba	19,800	22,900	300	2,800	400	0	46,200
Saskatchewan	9,900	36,100	300	100	400	700	47,500
Alberta	27,800	139,800	100	400	2,100	300	170,500
British Columbia	59,200	76,200	7,400	7,100	1,300	0	151,200
Total	504,800	601,000	121,100	97,200	11,300	1,300	1,336,700

Note: Environment data taken from (Environment Canada, 2011)

Table 2-2: Electricity and Natural Gas End Use Consumption and Related Greenhouse Gas Emissions by Sector, Toronto, ON

Market Sector	Electricity		Natural Gas		
	Consumption (GWh/yr)	GHG Emissions (Mt/yr)	Consumption (Mm3/yr)	GHG Emissions (Mt/yr)	Total GHG Emissions (Mt/yr)
Commercial	14,806	3.61	1,303	2.63	6.24
Industrial	2,553	0.62	589	1.19	1.81
Residential	7,658	1.87	2,270	4.58	6.45
Other	511	0.12	42	0.08	0.21
Total	25,527	6.23	4,205	8.49	14.72

Note: Taken from (Toronto city, 2009)

Table 2-2 provides a sector-by-sector analysis of energy use in Toronto and corresponding greenhouse gas emission. Electricity and natural gas end-use in Toronto accounts for approximately 60% of the city's entire greenhouse gas emissions. As Table 2-2 illustrates, the residential sector is the second largest user of electricity at 30% and the largest consumer of natural gas at 54% (Toronto's Sustainable Energy Strategy, 2009).

As a result, the residential sector in Ontario and Canada is facing an urgent need to reduce its primary energy that is being consumed by the existing residential buildings.

In light of this the following studies (Gurjot & Fung, 2011) (Haines, et al., 2007) (Dong,et al., 2005) (US Department of Energy, 2005), form the basis of this study. Consider the following points from the literature:

Gurjot & Fung, 2011, stated that the case with domestic hot water (DWH) heating systems includes two- panel solar systems with electric and gas backup tanks, modulating gas combo boilers, on –demand gas water heaters, and conventional electric and gas hot water tanks. This study considers fuel consumption, greenhouse gas (GHG) emissions, and 30- year life-cycle costs for over 432 sensitivity scenarios, and shows how consumption varies for a variety of DHW systems. The models developed in this study will be used to model the DHW for the research project also.

Retrofitting the residential sector is recommended for upgrades such as DHW and insulation upgrades. It is important to know that the relevance of the building code is a major factor in any residential upgrades. In a study that shows consistency with the idea above, Haines, et al., (2007) compare the implication of the variance building code standards for a detached single-family residential dwelling located in Toronto, Ontario. It compares three standards:

1) Current Ontario Building Code
2) R2000 Building Code ≈ 30 percent more efficient space heating than OBC
3) Author Designed ≈ 30 percent more efficient space heating than R2000

Studies were performed to calculate lifetime economic costs under a variety of natural gas pricing scenarios. In addition to this, a Life Cycle Assessment (LCA) and environmental impacts are considered. By building to high-efficiency standards, greenhouse gas emissions can be reduced by up to one third and, total lifetime costs are reduced anywhere from $500 CAD to $60,000 CAD depending on the natural gas pricing scenario.

Finally the relevance of least cost upgrades, selection of upgrades, and code implication have been considered. It is important to simulate these in order to determine the energy consumption of the varying scenarios. For this study, Transient Simulation Systems (TRNSYS) software was used. However, to show how effective this modeling software is over other packages, the study referenced here shows the validity of using such transient software to obtain an accurate building simulation model. TRNSYS is well validated software (US Department of Energy, 2005). The study referenced here shows how effective this modeling software is and the validity of using such transient software to get an accurate building simulation model. In 2005, a joint report was issued by the US DOE, Energy Systems Research Unit, University of Wisconsin-Madison, and National Renewable Energy Laboratory, which contrasted the performance capabilities of various building energy performance simulation programs. This paper provides an overview of over twenty simulation programs of which TRNSYS was also analyzed. This report was commissioned to allow both industry, and academia to determine the capabilities of building simulation software and to benchmark applications currently available on the market. The focus of this report was to provide users an assessment tool for determining which application is best suited for their needs. The report considered a broad range of software capabilities from the user interface, to simulation engines and code. This comparison was based on information provided by the program developers and a limited peer review process. The analyses were performed with 14 key indicators which included:

1) General Modeling Features
2) Zone Loads
3) Building Envelope, Day lighting and Solar
4) Infiltration, Ventilation, Room Air and Multi zone Airflow
5) Renewable Energy Systems
6) Electrical Systems and Equipment
7) HVAC Systems
8) HVAC Equipment
9) Environmental Emissions

10) Climate Data Availability
11) Economic Evaluation
12) Results Reporting
13) Validation
14) User Interface, Links to Other Programs, and Availability

As a result of these validations, TRNSYS was chosen for this study. There have been numerous studies performed using TRNSYS energy modeling software, by the CCHT, such as (Armstrong, et al., 2009) which was discussed previously in this literature review.

2.2 History of Building Codes in Canada

The National Building Code of Canada is the model building code of Canada. It is issued by the Institute for Research in Construction (IRC), a part of the National Research Council of Canada. In 1941 the federal government published the first National Building Code or NBC. This was adopted by the various provinces in Canada during the next 20 years. Around 1960 there was a revision on the NBC, followed by subsequent revisions approximately every five years. Some provinces still use the NBC whilst others have introduced their own building codes (NRCan, 2005). To meet their needs, most of the provinces in Canada such as British Columbia, Alberta, Saskatchewan, Ontario, Quebec and Nova Scotia have developed and published their own building codes. Provinces in Atlantic Canada (i.e., Newfoundland, New Brunswick and Prince Edward Island) have adopted the national building code (NBC) as provincial building code (National Research Council of Canada [NRCC], 2009). The specifications of provincial building codes were based on the NBCC and the Model National Energy Code for Buildings[1] [MNECB] (NRCC, 2009) (Dembo, 2011).

The history of building codes in Ontario dates back to the constitution of Canada, which included the regulation of building construction as a provincial responsibility (NRCan, 2005). Ontario introduced its own building code in 1975 (Government of Ontario, 2011), which was based on NBC. The development and history of the codes is complex but is shown in Figure 2-1with revision dates in Table 2-3. Ontario is currently changing its building code for 2012 (Government of Ontario, 2011) which will become the standard for residential building codes in Ontario.

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[2] MNECB only applies to Ontario (NRCC, 2009)

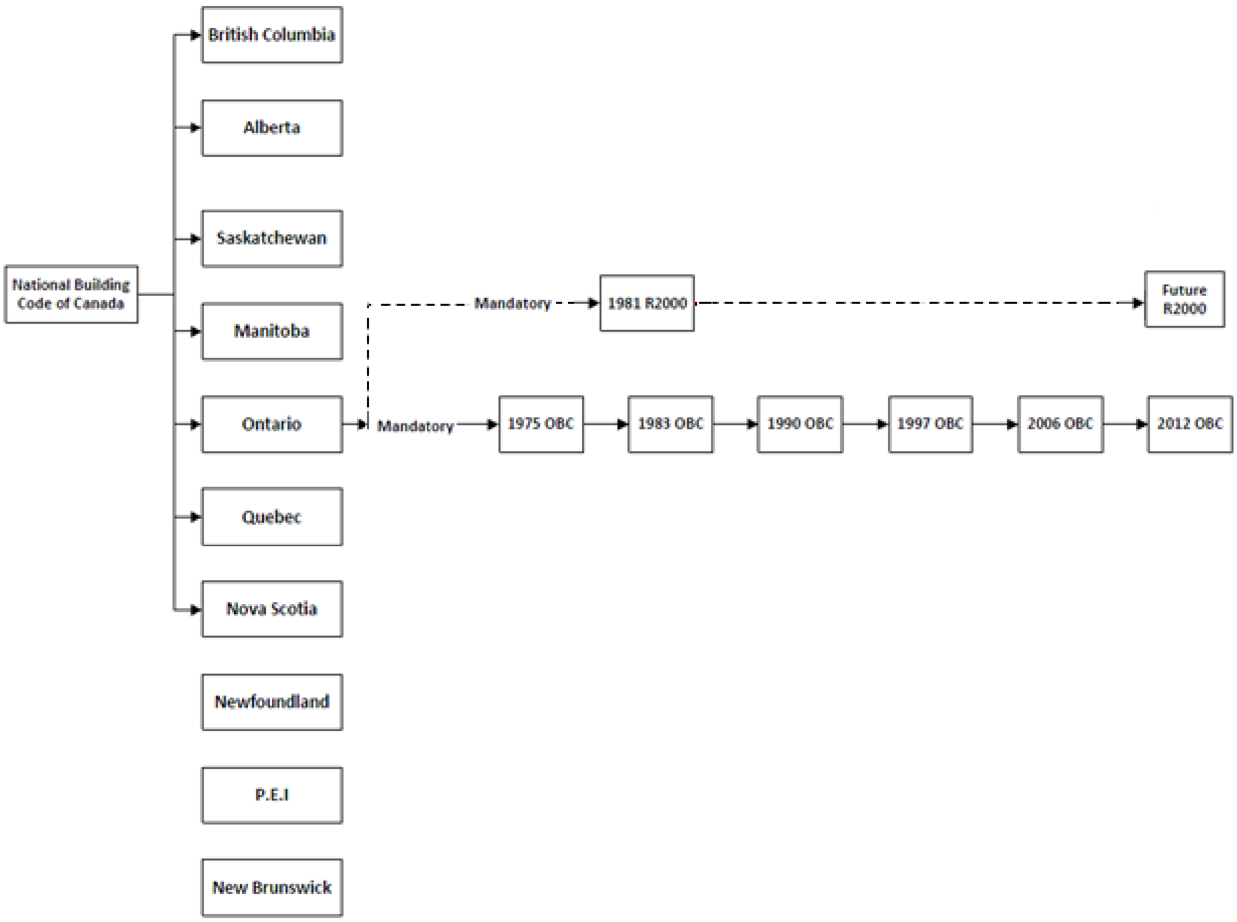


Figure 2-1: National and provincial building codes in Canada and development of Ontario Building Code

Table 2-3: 1975 – 2012 Ontario Building Code Amendment History

Item	Building Code Edition	Date Filed	Effective Date
1	1975 Building Code	November 24, 1975	December 31, 1975
2	1983 Building Code	September 15, 1983	November 30, 1983
3	1986 Building Code	July 18, 1986	October 20, 1986
4	1990 Building Code	July 30, 1990	October 1, 1990
5	1997 Building Code	November 3, 1997	April 6, 1998
6	2006 Building Code	June 28, 2006	December 31, 2006
7	2012 Building Code	December 21, 2009	December 31, 2011

Note: Date take from (Government of Ontario, 2006)

The R-2000 energy efficiency standard is another note of interest. The introduction of R-2000 occurred in 1981 by NRCan in partnership with the Canadian Home Builders Association (CHBA, 2011) and was formalized as a standard in 1982. Notably, the R-2000 standard is a voluntary standard to exceed OBC building code requirements for energy efficiency, indoor air quality and environmental responsibility. In May 2008, the CHBA published an internal discussion paper proposing changes to the R-2000 standard so it would remain at the forefront as the reference model that influences other programs or initiatives; to date it remains as such. However, for the purposes of this study, the 2006 OBC will be the reference code for benchmarking. It should be noted that the OBC 2012 code and R-2000 standards have been considered in some areas of this research.

However, to illustrate the historical trends of changes made to the OBC over the past 35 years, Table 2-4 summarizes the minimal thermal resistance (RSI) of insulation to be installed in a house as specified by 1997 and 2006 Building Codes, including the 2012 OBC and the R-2000 codes, and the as built condition of the CCHT reference house.

Table 2-4: Comparison of required insulation (RSI) of Ontario Building Codes 1997 - 2012

Component	Units	As Built	1997 Building Code Gas	2006 Building Code Gas	% of Increase 1997-2006	2006 Building Code Electric	R2000	2012 Building Code Gas	2012 Building Code Electric
Ceiling with Attic Space Minimum RSI R-Value	m^2K/W	8.6 R49	5.40 R31	7.24 R41	34.10%	8.81 R51	8.81 R50	8.81 R50	8.81 R50
Ceiling without Attic Space Minimum RSI R-Value	m^2K/W	8.6 R49	3.52 R20	5.21 R30	48.00%	5.21 R30	8.81 R50	5.46 R31	5.46 R31
Exposed Floor Minimum RSI R-Value	m^2K/W	4.4 R25	4.40 R25	4.70 R27	6.82%	4.70 R27	-	5.46 R31	5.46 R31
Walls Above Grade Minimum RSI R-Value	m^2K/W	3.5 R20	3.00 R17	3.80 R22	26.67%	R32	-	5.11 R29	5.11 R29
Basement Walls Minimum RSI R-Value	m^2K/W	3.5 R20	2.4 R14	2.4 R14	0%	3.63 R21	-	.88 R5	3.52 R20
Below Grade Slab Entire Surface > 600 mm Minimum RSI R-Value	m^2K/W	-	1.41 R8	1.76 R10	24.82%	2.11 R12	-	1.76 R10	1.76 R10
Edge of Below Grade Slab < 600 mm Minimum RSI R-Value	m^2K/W	-	1.41 R8	-	-	-	-	1.76 R10	1.76 R10
Windows & Sliding Glass Doors Maximum U-Value	W/m^2K	1.69	3.3	2	-	2	0.5	1.6	1.6
Space Heating Equipment	Minimum AFUE	91%	90%	90%	-	-	-	90%	-
Electric Space Heating Equipment	Minimum η	-	-	-	-	90%	-	90%	78%
Heat Recovery Ventilator (HRV)	Minimum η	80%	-	-	-	-	-	-	75
Domestic Hot Water Heater	EF	0.67	0.57	0.57	-	0.57	0.58	0.57	0.57
Air Conditioning Minimum	SEER	12	-	-	-	-	10.5	-	-

Note: Environment data taken from (Government of Ontario, 2011) *for OBC,* (CCHT, 2011) *for the As Built, &* (CHBA, 2011)*for the R2000 codes respectively*

The table includes items that affect the building envelope such as insulation, HVAC equipment, and domestic hot water heating for Zone 1 buildings with heating degree days (HDD) ≤ 4000 °C-days, which Toronto falls into.

Based on the 2006 Census, the most populated provinces in Canada were indicated in Figure 2-2. Ontario with approximately 13 million residents is the most highly populated province in Canada followed by Quebec (7.7 million); British Columbia (4.3 million); Alberta (3.5 million)Statistic Canada, 2011) (Dembo, 2011).

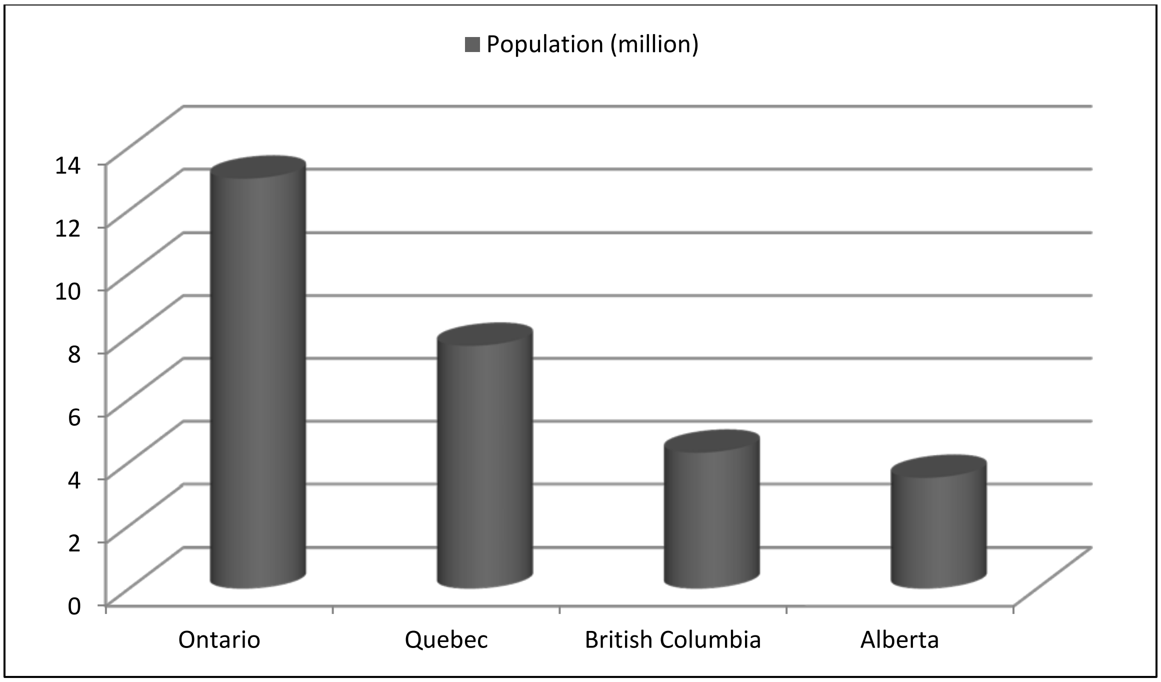


Figure 2-2: Population of provinces in Canada, 2007 (Dembo, 2011)

The GTA supports a population of 5.623 million shown in Table 2-5, with HDD of 4066°C-days. As mentioned, proposed changes for the 2012 code have provided numerous prescriptive packages for a variety of residential scenarios for construction. These scenarios take into account various HVAC systems, waste heat recovery packages, envelope changes, and other prescriptive measure to improve the building envelope. The 2006 OBC does not have the prescriptive package selection choices, but for the purposes of this study, the 2012 OBC will not be considered, and all model standards will be based on the current or 2006 OBC.

Table 2-5: Population of Major Canadian Cities by Heating Degree Days

Province	Selected City	Population [1]	Climate [2]	Provincial Average
		[Person (thousands)]	[Heating degree-days below 18°C (HDD)]	[HDD]
		() = Overall in Canada	°C-days	
British Columbia	Vancouver [3]	2328.0 (3)	2926.5	3225.7
	Summerland	N/A	3524.8	
Alberta	Edmonton	1155.4 (6)	5708.2	5154.3
	Lethbridge	N/A	4600.3	
Manitoba	Winnipeg [3]	742.4 (8)	5777.5	6187.8
	The Pas	N/A	6598.1	
Saskatchewan	Saskatoon [3]	257.3 (17)	5852.4	5600.2
	Swift Current	N/A	5347.9	
Ontario	**Toronto [3]**	**5623.5 (1)**	**4065.7**	**4293.3**
	Ottawa	1220.7 (5)	4520.8	
Quebec	Montreal [3]	3814.7 (2)	4518.7	5397.8
	Sept Iles	N/A	6276.9	
New Brunswick	Fredericton	N/A	4750.7	4750.7
Newfoundland	St. John's [3]	187.6 (21)	4881.5	4881.5
Nova Scotia	Halifax [3]	398.0 (13)	4367.2	4367.2
Prince Edward Island	Charlottetown	N/A	4715.3	4715.3

Note: Environment data taken from (Enviroment Canada, 2011)

2.3 Life Cycle Assessment (LCA) Methodology

Life Cycle Assessment (LCA) as shown in Figure 2-3 (Dembo, 2011) is a quantitative technique to assess environmental impacts associated with all the stages of a product's life (Dong,et al., 2005).

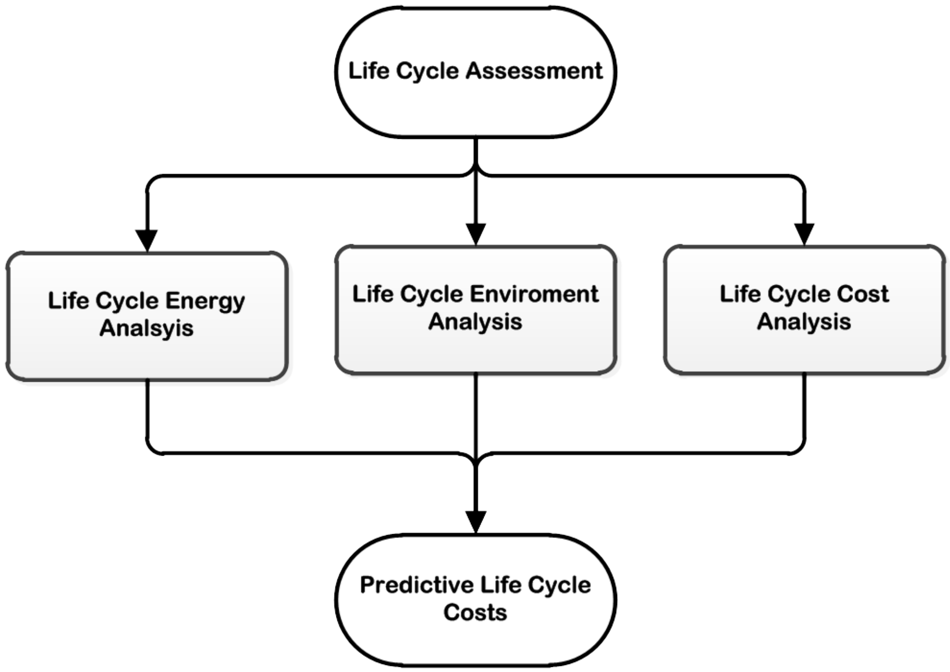


Figure 2-3: Life Cycle Assessment (LCA) Methodology (Dembo, 2011)

Essentially there are inputs and outputs associated with each stage. The inputs are comprised of energy, water, and raw materials, whilst the outputs are comprised of gaseous, liquid, and solid wastes as shown in Figure 2-4. The stages consist of but are not limited to raw material extraction, materials processing, manufacture, distribution, use, repair, maintenance, and disposal or recycling costs. LCA uses the triaging of the three contributors - energy, environment and cost - to predict the overall cost of a product. These LCA factors have been summarized below in further detail.

2.3.1 Life cycle energy analysis

Life Cycle Energy Analysis (LCEA) (Wolfgang, 1997), (Dong,et al., 2005).: LCEA is an approach in which all energy inputs to a product are accounted for, not only direct energy inputs during manufacture, but also all energy inputs needed to produce components, materials and services needed for the manufacturing process. An earlier term for the approach was energy analysis.

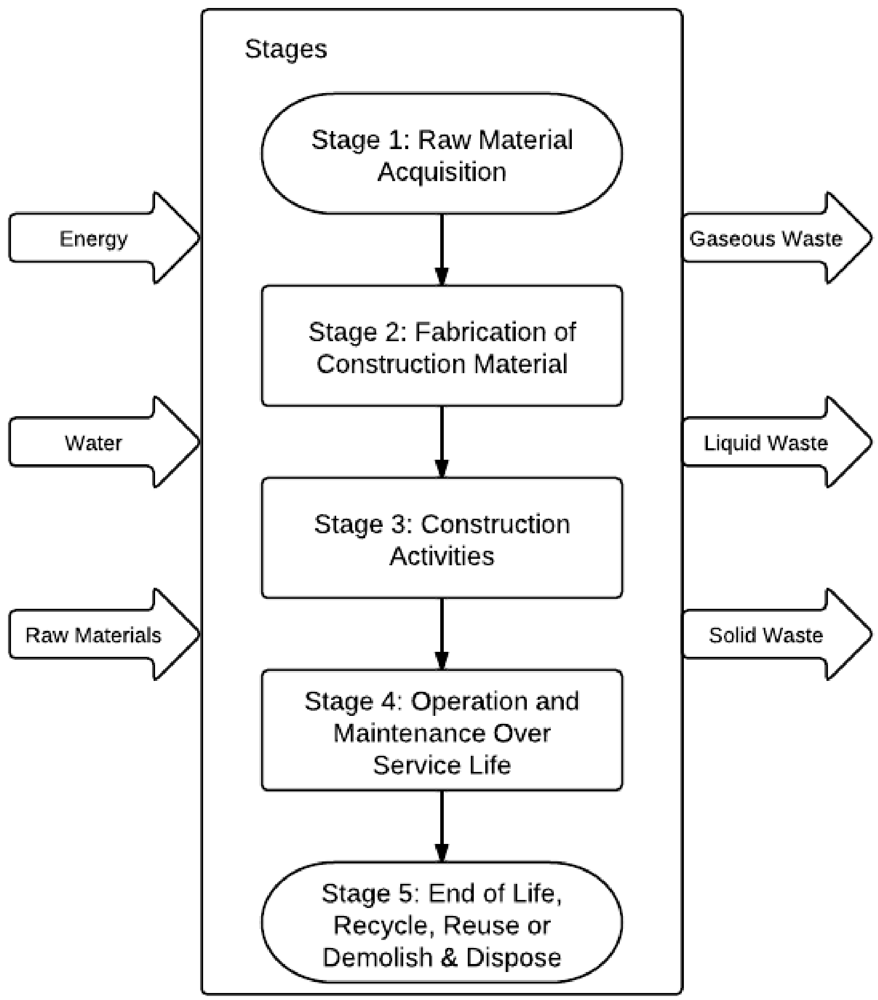


Figure 2-4: Stages of life Cycle of a Building and Environmental Metrics considered in LCA

Note: Flow Chart taken from (Dong,et al., 2005)

2.3.2 Life cycle environmental analysis

Life Cycle Environment Analysis (Dong,et al., 2005): Life cycle environment analysis is an approach in which all environmental contributors are accounted for in the life cycle of a product. This includes the resource extraction phase to the use phase and finally to the disposal phase. A case in point: trees produce paper, which can be recycled into low-energy production cellulose or fiberized paper insulation. This insulation can then be used in the ceiling of a home for 40 years, saving 2,000 times the fossil-fuel energy used in its production. After 40 years the cellulose fibers are replaced and the old fibers are disposed of, possibly incinerated. All inputs and outputs are considered for all the phases of the life cycle.

2.3.3 Life cycle cost analysis (LCCA)

Life Cycle Cost Analysis is a method to assess the total cost of a product of facility from birth to death. It takes into account all costs of acquiring, owning, and disposing of a product, building or building system. The costs include but are not limited to research, engineering, development, borrowing, inflation, interest, material, production, equipment, salvage and warranty costs. Present value, future value and other engineering economics methods are employed to contrast and compare various economic indicators.

2.4 Optimization Technique

2.4.1 Brute force sequential search (BFSS) method

Brute force sequential search (BFSS) is a trivial but very general problem-solving technique that consists of systematically enumerating all possible candidates for the solution and checking whether each candidate satisfies the problem's statement. For example, a brute-force algorithm to find the divisors of a natural number *n* is to enumerate all integers from 1 to the square-root of *n*, and check whether each of them divides *n* without remainder. The brute-force search is simple to implement, and will always find a solution if it exists. However, its cost is proportional to the number of candidate solutions, which, in many practical problems, tends to grow very quickly as the size of the problem increases. Therefore, brute-force search is typically used when the problem size is limited, or when there are problem-specific heuristics that can be used to reduce the set of candidate solutions to a manageable size. The method is also used when the simplicity of implementation is more important than speed (Wikipedia, 2011). In order to identify the most cost-effective energy efficiency upgrades, the brute force sequential method was used in this report.

2.5 Building Energy Simulation

To achieve the energy efficiency goal, architects and building designers require design tools for analysing and understanding the complex behaviour of building energy use. Building energy simulation is a useful tool in determining how much energy a building, whether new or existing, is predicted to consume over the course of a year (Solar Energy Laboratory, 2011). Literally hundred examples of energy simulation softwares have been developed for use in the building industry (Karlsson, et al., 2007). All these simulations determine the energy consumption of a structure, equipment.

TRNSYS is one of a group of capable building energy simulation program in energy modeling. TRNSYS was originally developed at the Solar Laboratory within the University of Wisconsin-Madison, and made commercially available in 1975 (Solar Energy Laboratory, 2011). It is one of the most advanced programs for the simulation of active solar systems sponsored by the U.S. DOE (US Department of energy, 2005). TRNSYS components (also referred to as TYPES) is based upon the notion of breaking larger problems into smaller modularized problems. This allows for many TYPES to be built up into larger more complex problems eventually creating a building model. The two main interfaces TRNSYS are TRNBuild (Building input data) and TRNSYS Simulation Studio (Simulation engine).

TRNSYS has been used extensively in both the academic and commercial sectors and numerous studies and papers have been written on its validity. The CCHT house has also been modeled using TRNSYS (Haddad, et al., 2009) and will be used as a base model, with the addition of the prescriptive upgrades being considered in this study.

Chapter 3

3 Methodology

3.1 Overview

The objective of this report is to present the methodology developed to identify the upgrade solutions with the lowest life cycle cost that could be applied to currently practice new housing. These solutions must meet various levels of thermal performance while considering:

1) The use of local materials and resources
2) Ease of construction
3) Adoption by Canadian housing industry through the optimization in energy and costs using life cycle cost analysis (LCCA)
4) A brute force sequential search (BFSS) method.

Figure 3-1 shows the overview of the proposed methodology developed to achieve the objective stated above. The description of each process is summarized as follows.

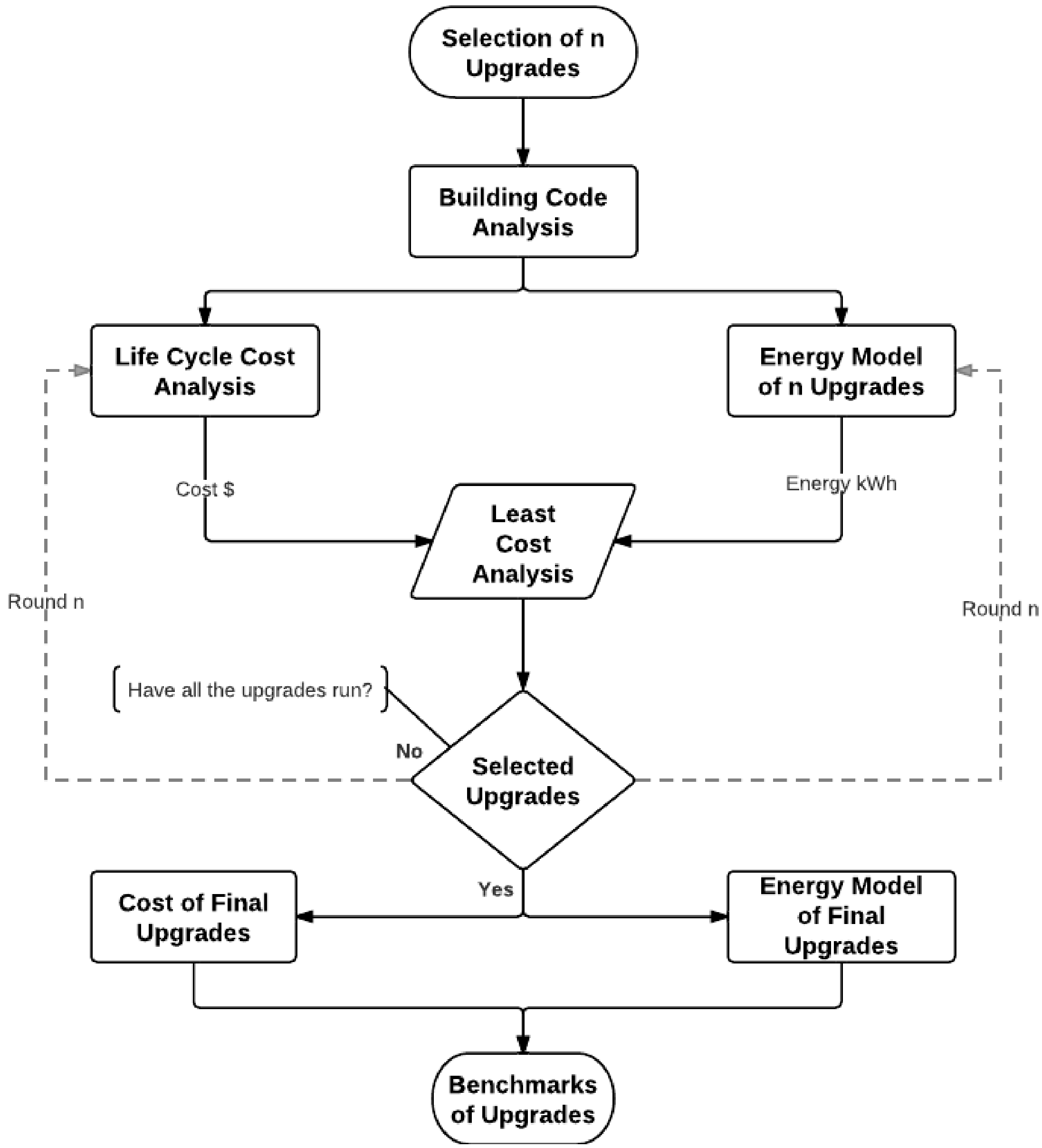


Figure 3-1: Methodology of Least Cost Analysis for Residential Upgrades

3.2 Building Type

The Canadian Centre for Housing Technology (CCHT) house (CCHT, 2011) built in 1998 is jointly operated by the National Research Council (NRC, 2005), Natural Resources Canada (NRCan, 2006), and Canada Mortgage and Housing Corporation (CMHC, 2011). The twin houses offer a real time monitored environment with simulated occupancy to assess the performance of the residential energy technologies. The CCHT house is an existing two-storey single-family dwelling with an attached two-car garage (Dembo, 2011) and was used to represent a typical Canadian new house for this report. Table 3-1 summarizes the characteristics of the house.

Table 3-1: Specification of the Reference House (Dembo 2011)

CCHT Research House specifications	
Floor Area	210 m^2
Internal ceiling height	5.48 m
Total space volume	1198 m^3
Total windows area	35 m^2
Windows to wall ratio	22%

The ratio of windows to the wall in all directions is shown in Table 3-2.

Table 3-2: Windows to wall ratio of the research House (Dembo, 2011)

Windows to the wall ratio	
South facing (front)	34%
West facing	5%
North facing	24%
East facing	16%

Figure 3-2 shows the front orientation of the CCHT Twin Research Houses in Ottawa, ON.

Figure 3-2: The CCHT Twin Research Houses, Test House (left), Reference House (right) in Ottawa, ON (CCHT, 2011)

The building is limited to a south-north orientation, maintaining the original architectural configuration of the reference house. Therefore, the implication of other orientations, as well as the impacts of having exterior shading to reduce solar radiation will be eliminated in this study. Occupancy was based on the reference house having the simulated occupancy of two adults and two children. The following assumptions should be noted for the TRNSYS building simulation models:

The ventilations rates were set as:

1) Mechanical Ventilation = 0.1 ACH
2) Natural Infiltration = 0.23 ACH
3) Total Infiltration & Ventilation = 0.33 ACH

The seasons were set as:

1) Heating Season 1: Jan 1st (0 Hrs.) – May 1st (3400 Hrs.)
2) Cooling Season: May 1st (3400 Hrs.) – October 31st (6575 Hrs.)
3) Heating Season 2: October 31st (6575 Hrs.) – December 31st (8760 Hrs.)

The set point temperatures:

1) Heating: 22°C ±1°C Dead band
2) Cooling: 25°C ±1°C Dead band

3.2.1 Building code modeling methodology

The reference model in this study is taken from the CCHT model home with some alterations. Figure 3-3 describes the changes that were done to the base CCHT model in order to use it for this study. Essentially six steps were performed to the original TRNSYS building simulation model (Figure 3-3) which involved:

1) As Built: This was the as-built model used by (Armstrong, et al., 2009), which was validated against the current CCHT home.

2) Location Model: Modifications were made to the CCHT model to included location, weather data, heating / cooling / lighting / occupancy / and DHW schedules for a typical four person residency of two adults and two children.

3) 2006 OBC Base Case: Modified to include all 2006 OBC criteria as shown in Table 2-4 to become the reference model for all further studies. This is the *"Baseline Reference Case"* indicated by upgrade label A in all subsequent tables.

4) TRNSYS Unlimited Model: This model is the previous 2006 OBC case. It is modified to determine the maximum heating and cooling loads required to heat / cool the housing unit. This is the *"TRNSYS Unlimited Case"* indicated as *TREF* in all subsequent tables.

5) Upgrade Model / n Upgrade Models: Modifications to the 2006 OBC Case to include each specific prescriptive upgrade. This resulted in 31 separate upgrade models, which will be shown in all subsequent tables.

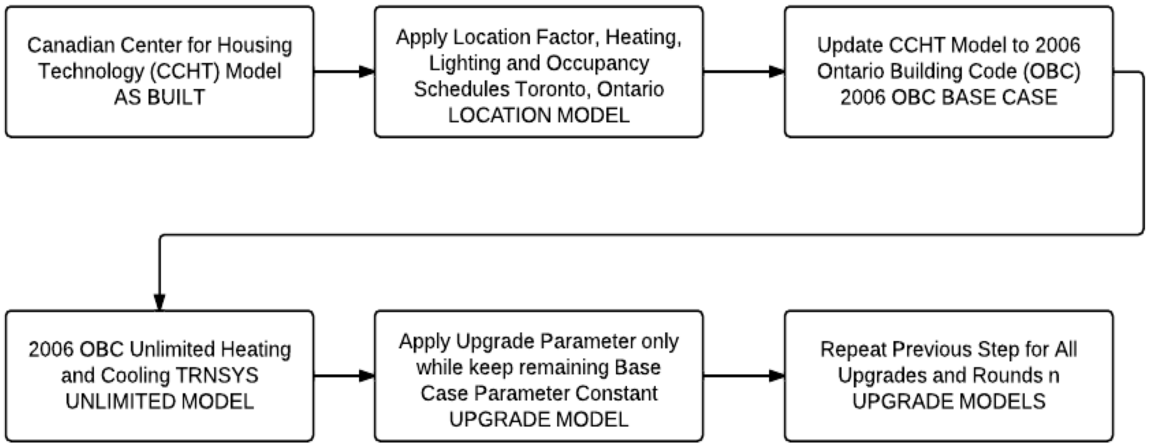


Figure 3-3: Building Code Modeling Methodology

In Addition, Table 3-3 summarizes some of the assumptions that were used in TRNSYS building simulation models.

Table 3-3: CCHT TRNSYS Modeling Parameters, for Toronto, Ontario

TRNSYS Models and Reference Cases				
Parameter	Unit	TRNSYS Case 1	TRNSYS Case 2a	TRNSYS Case 2b
Building Code Parameters				
Building Model	-	CCHT	CCHT	CCHT
Building Code	-	2006 OBC	2006 OBC	2006 OBC
Set Point Heating	°C	22	22	22
Set Point Cooling	°C	25	25	25
Temperature Dead Band	°C	±2	±2	±2
Software Time Step	Min	10	10	10
Weather Parameter				
Weather Location	-	Metro Toronto	Metro Toronto	Metro Toronto
HDD Below 18°C	-	4197	4197	4197
CDD	-	318	318	318
TDD	-	4515	4515	4515
Domestic Hot Water				
Tank Volume	L	225	225	225
Set Point Temperature	°C	55	55	55
Ground Water Temperature	°C	18	18	18
Infiltration				
Natural	ACH	0.10	0.10	0.10
Mechanical	ACH	0.23	0.23	0.23
Total	ACH	0.33	0.33	0.33
Occupancy Adults	-	2	2	2
Occupancy Time	%	50	50	50
Appliance & Lighting				
Interior Lighting	kWh/day	3	3	3
Appliances	kWh/day	14	14	14
Other Appliances	kWh/day	3	3	3
Exterior use	kWh/day	4	4	4
Total Consumption	kWh/day	24	24	24
Total Consumption	kWh/year	8760	8760	8760

3.3 Energy Modeling

When energy efficiency measures are added to residential housing upgrades, two opposing events variables will be influenced economically (Farahbakhsh, et al., 1997) which include:

1) Cost
2) Consumption

These two main variables need to be determined in order to achieve optimal upgrades in least cost analysis (LCA). Building energy simulation and modeling is a technique that was used to determine the energy consumption of CCHT house. Using building energy simulation software is a theoretical method to perform a detailed thermal analysis or energy model of the building. This is an acceptable technique (American National Standards Institute, 2011; Underwood & Yik, 2004) as shown in Table 3-4.

Table 3-4: ASHRAE's Classification of Methods for the Thermal Analysis of Buildings

Method	Forward	Inverse	Hybrid	Comments
Steady State Methods				
Simple Linear Regression		X		One dependent parameter, one independent parameter. May have slope and y-intercept.
Multiple Linear Regression		X	X	One dependent parameter, multiple independent parameters.
Modified Degree Day	X			Based on fixed reference temperature of 65F
Variable Base Degree Day Method	X			Variable reference temperature
Traditional ASHRAE bin method and inverse bin method	X	X	X	Hours in temperature bin times load for that bin.
Change Point Models: 3 parameter (PRISM CO, HO); 4 Parameter, 5 Parameter (PRISM HC)		X	X	Uses daily or monthly utility building data and average period temperatures.
ASHRAE TC 4.7 modified bin method	X		X	Modified bin method with cooling load factors.
Dynamic Methods				
Thermal Network	X	X	X	Uses equivalent thermal parameter (inverse mode)
Response Factors	X			Tabulated or as used in simulation programs.
Fourier Analysis	X	X	X	Frequency domain analysis convertible to time domain.
ARMA Model		X		Autoregressive Moving Average Model
ARMA Model		X		Multiple-input autoregressive moving average model
BEVA, PSTAR	X	X	X	Combination of ARMA and Fourier series includes loads in time domain.
Model Analysis	X	X	X	Building, described by diagonal zed differential equation using nodes.
Differential Equation		X		Analytical linear differential equations.
Computer Simulation (DOE-2, BLAST)	X			Hourly simulation program with systems models.
Computer Emulation (HVACSIM+TRNSYS)	X			Sub-hourly simulation programs.
Artificial Neural Networks		X	X	Connectionist models

Haddad, et al., (2009) built an energy model for the CCHT house using the transient simulations system software known as TRNSYS. “TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. TRNSYS is used by engineers and researchers to validate new energy model concepts, from simple domestic systems to the design and simulation of multi-zoned buildings and their associated equipment. One of the benefits in using TRNSYS is its open-source, modular structure. Standard TRNSYS components include controllers, electrical, heat exchangers, HVAC, hydrogen systems, hydroids, loads and structures, output, physical phenomena, solar thermal collectors, thermal storage, utility, and weather data reading and processing” (Solar Energy Laboratory, 2011).

Building simulation model essential imposes a modeling approach that is described in Figure 3-4 and Figure 3-5. It is essential that an iterative approach with the conceptual model at the tier, with the building envelope and loads are taken into the TRNSYS building and simulation model. The branches of the two main tiers are quite extensive; however, they are composed of the building envelope and building loads variables.

Building envelope generally refers to those building components that enclose condition spaces and through which thermal energy is transferred to or from the outdoor environment (Turner & Doty, 2007). The thermal energy transfer rate is referred to as the “heat loss” or “heat gain” when trying to maintain a building temperature that is greater or less than the outdoor temperature (McQuiston, et al., 2005). The mechanical heating or cooling loads in a building are dependent upon the various heat gains and losses experienced by the building, including solar and internal heat gains or losses experienced by transmission through the building envelope and by infiltration or ventilation of outside air (Turner & Doty, 2007). Building loads consist of the systems that are employed to maintain the desired temperature of the building and associated systems. The models that were created accounted for all contributors shown in the subsequent figure, resulting in a robust building simulation model. This approach was used for all prescriptive upgrades for the energy model. This approach resulted in as many models as there were upgrade scenarios.

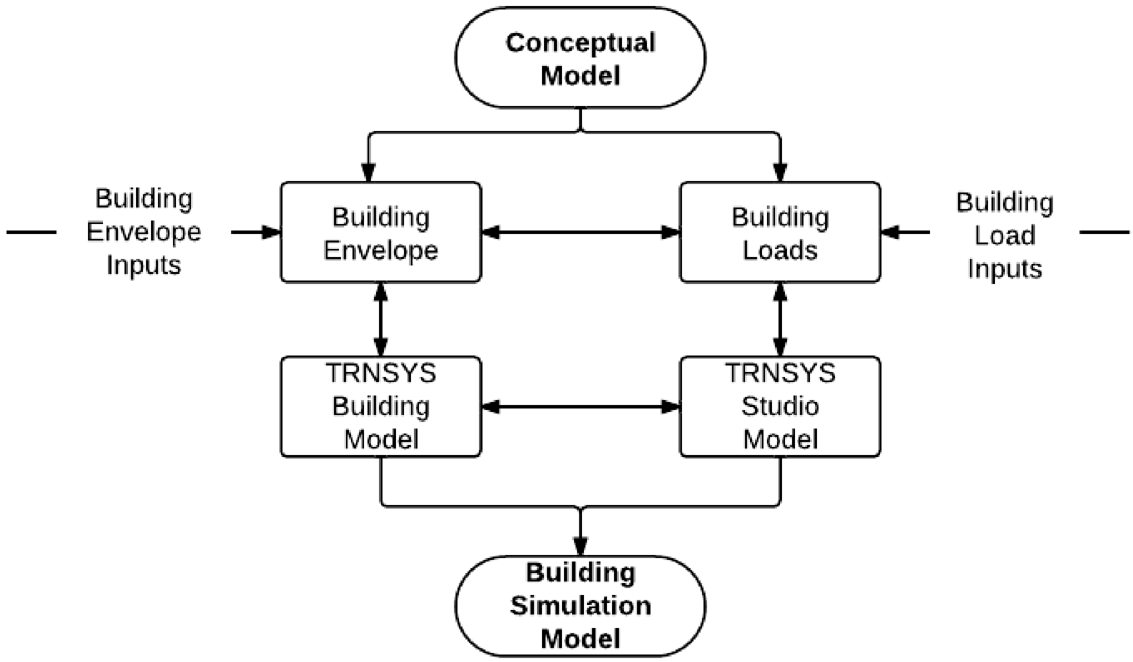


Figure 3-4: TRNSYS Energy Modeling Process Flow

But what does theoretical model look like, and how do they function with respect to other systems, such as controllers and thermostats? Figure 3-6 shows a typical example of a building simulation model that can be created in TRNSYS.

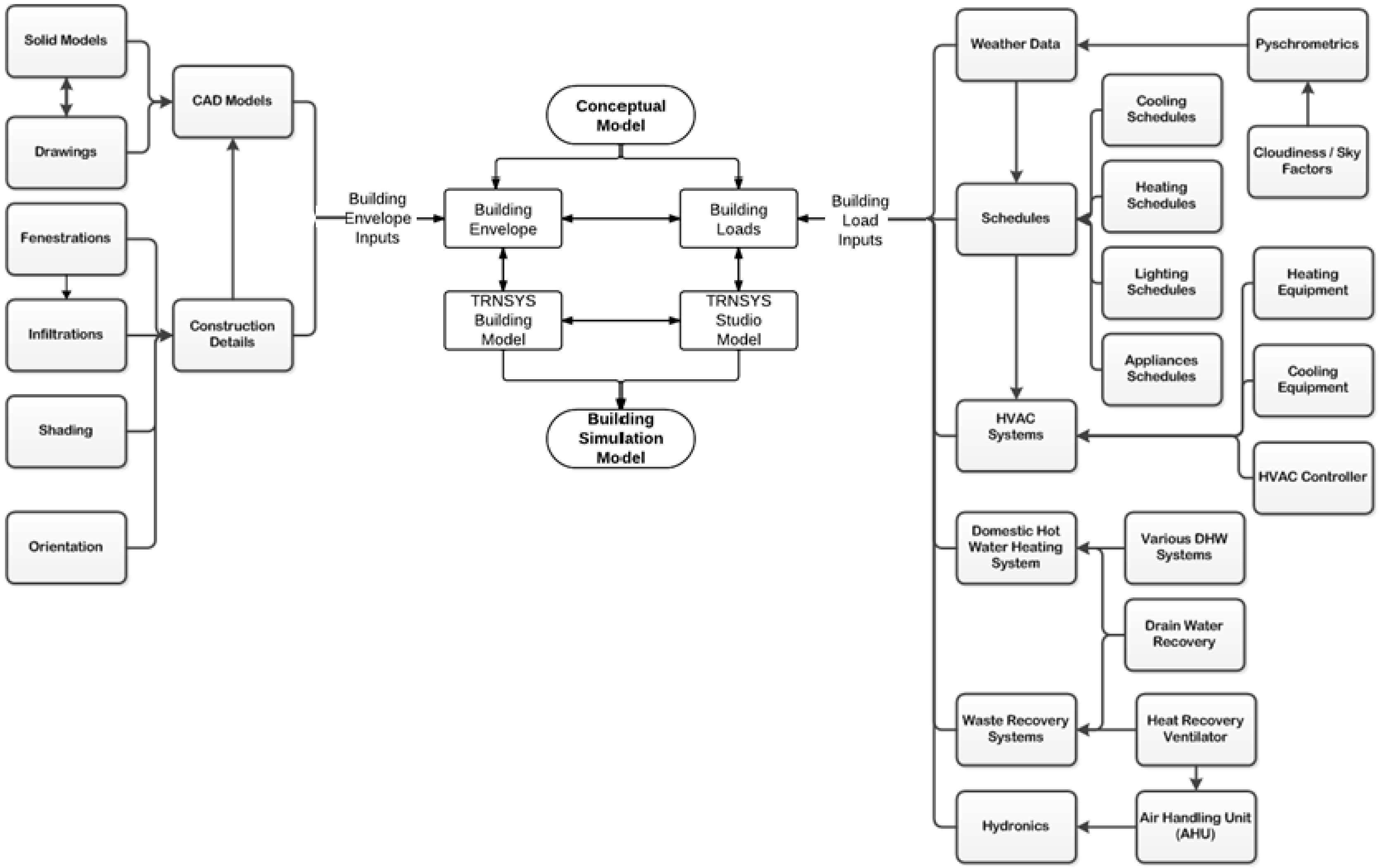


Figure 3-5: TRNSYS Energy Modeling Process Flow Detailed

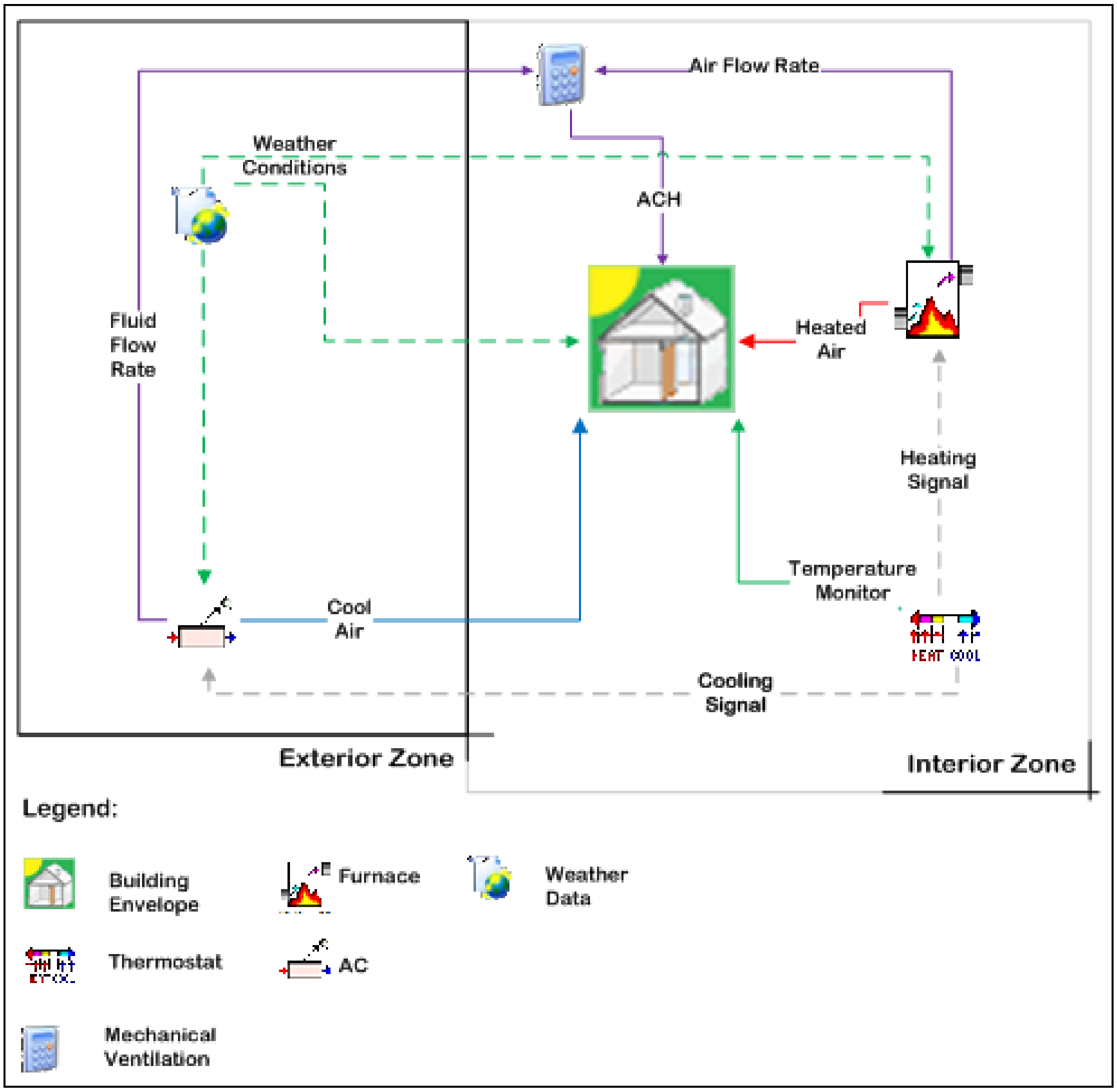


Figure 3-6: Building Simulation Model for Furnace & AC HVAC Systems

TRNYS being transient simulation software requires a time step input in order to determine the accuracy of the convergence of the solution. In order to validate the model, a baseline reference case was run at a variety of time steps in order to determine the validation of the model against previous studies in HOT2000 (Dembo, 2011), which will also be shown in the sensitivity analysis of this study. However, an initial time step of half a minute was originally run, followed by 1, 5, 10, 12, 15, 20, 30, and 60 minutes respectively. File size, heating load, cooling load, exhaust fan consumption, furnace fan consumption, were changing in the study, whilst DHW, appliances & lighting loads were all calculated based separately (Dembo, 2011; Gurjot & Fung,

2011) outside the TRNSYS model. In Table 3-5, it can be seen that the convergence based on the reference time step (0.5 minutes) falls quickly outside of convergence of greater than one percent after a time step of five minutes. For all subsequent studies, a time step of five minutes was used to ensure the accuracy of the transient model to the baseline reference case.

Table 3-5: Time Step Convergence Analysis baseline Reference Case for Toronto, Ontario

Case 1	Time Step	File Size	Heating Load	Cooling Load	Exhaust Fan	Furnace Fan	DHW	Appliances Lighting	Total Consumption
#	min	MB	kWh	kWh	kWh	kWh	kWh	kWh	kWh
Ref	0.5	1GB	22,900	707	324	566	7,735	8,760	40,991
1	1	516	23,100	707	324	570	7,735	8,760	41,196
2	5	104	23,100	706	324	571	7,735	8,760	41,196
3	10	53	31,100	728	324	571	7,735	8,760	49,218
4	12	44	37,399	729	324	1,405	7,735	8,760	56,353
5	15	36	38,700	729	324	1,480	7,735	8,760	57,728
6	20	27	38,800	731	324	1,490	7,735	8,760	57,840
7	30	19	39,000	730	324	1,510	7,735	8,760	58,059
8	60	10	38,966	721	324	1,502	7,735	8,760	58,008
Case Convergence		Ref	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
		1	0.87%	0.00%	0.31%	0.71%	0.00%	0.00%	0.50%
		2	0.87%	0.14%	0.31%	0.88%	0.00%	0.00%	0.50%
		3	35.81%	2.97%	0.31%	0.88%	0.00%	0.00%	20.07%
		4	63.32%	3.13%	0.35%	148.25%	0.00%	0.00%	37.48%
		5	69.00%	3.11%	0.31%	161.48%	0.00%	0.00%	40.83%
		6	69.43%	3.39%	0.31%	163.25%	0.00%	0.00%	41.10%
		7	70.31%	3.25%	0.31%	166.78%	0.00%	0.00%	41.64%
		8	70.16%	1.99%	0.35%	165.42%	0.00%	0.00%	41.51%

3.4 Selection of Least Cost Upgrades

Selection of upgrades is the first step of the least cost analysis process. The selection of upgrades was based upon an extensive literature review and local builder's survey (Dembo, 2011). The main factors in the selection of upgrades were:

1) Cost effectiveness
2) Energy reduction potential

The proposed upgrade scenarios are classified into the following four main categories (Table 3-6), and broken down into eight more detailed categories in Figure 3-7. Essentially the upgrades fall within four major categories described below:

1) Building Envelope: The upgrades pertain to insulation upgrades in various areas of the home.
2) Ventilation: The upgrade is the heat recovery ventilator. It will affect the indoor air quality whilst taking advantage of energy reduction by improved climate control.
3) Cooling: Air-conditioning unit of SEER 14. It should be noted that it is not a requirement of the OBC code to have a cooling system; however, it is almost commonplace to have installed. For this study one included for comparison purposes of the reference case of 13 SEER.
4) Heating Gas Option: This category included HVAC systems and DHW systems running on gas as fuel source.
    (a) HVAC: A standard high efficiency gas furnace is included with varying AFUE efficiencies.
    (b) DHW: Water heating falls into three main types here, standard gas heated tank, solar domestic water heating, and drain water recovery.

Table 3-6: Proposed upgrades by Type, Category & Description

Upgrade Number	Upgrade Type	Upgrade	Upgrade Category	Upgrade Description	Acronym
A	Baseline Reference Case			2006 Ontario Building Code	BL
B	Case 1			GH6, AC1, GH1, AGW5, C1, EF1, BGW2, BS1, V1	C1
C	Case 2a			GH5, GH1, V1, AGW5, AC1, C1, EF2, BS1, BGW2	C2a
D	Case 2b			GH5, GH1, AGW5, AC1, V1, C1, EF2, BGW2, BS1	C2b
1	Building Envelope	UPG1	Ceiling	R50 Insulation	C1
2				R60 Insulation	C2
3		UPG2	Above Grade Wall	R22 Insulation	AGW1
4				R24 Insulation	AGW2
5				R27 Insulation	AGW3
6				R29 Insulation	AGW4
7				R24 Insulation @ 600 mm 24 inch O/C	AGW5
8				R26 Insulation @ 600 mm 24 inch O/C	AGW6
9				R29 Insulation @ 600 mm 24 inch O/C	AGW7
10				R40 Insulation	AGW8
11		UPG3	Below Grade Wall	R12 Insulation Exterior	BGW1
12				R20 Insulation	BGW2
13				R20 Insulation Exterior	BGW3
14				R22 Insulation	BGW4
15				R24 Insulation	BGW5
16				R24 Insulation ICFs	BGW6
17		UPG4	Exposed Floor	R29 Insulation	EF1
18				R31 Insulation	EF2
19		UPG5	Basement Slab	R12 Insulation	BS1
20				R20 Insulation	BS2
24	AHU	UPG7	Ventilation	Heat Recovery Ventilator HRV 70%	V1
25	HVAC	UPG8	Cooling	Air Conditioning: SEER 14	AC1
26		UPG9a	Gas Heating Options	Furnace w/ECM 90% AFUE	GH1
27	DHW			DHW Heater: @ 85% AFUE	GH2
28				DHW Heater: @ 90% AFUE	GH3
29				Solar Assisted DHW Heater: @ 85% AFUE	GH4
30				Solar Assisted DHW Heater: @ 90% AFUE	GH5
31				Drain Water Heat Recovery @ 55%	GH6

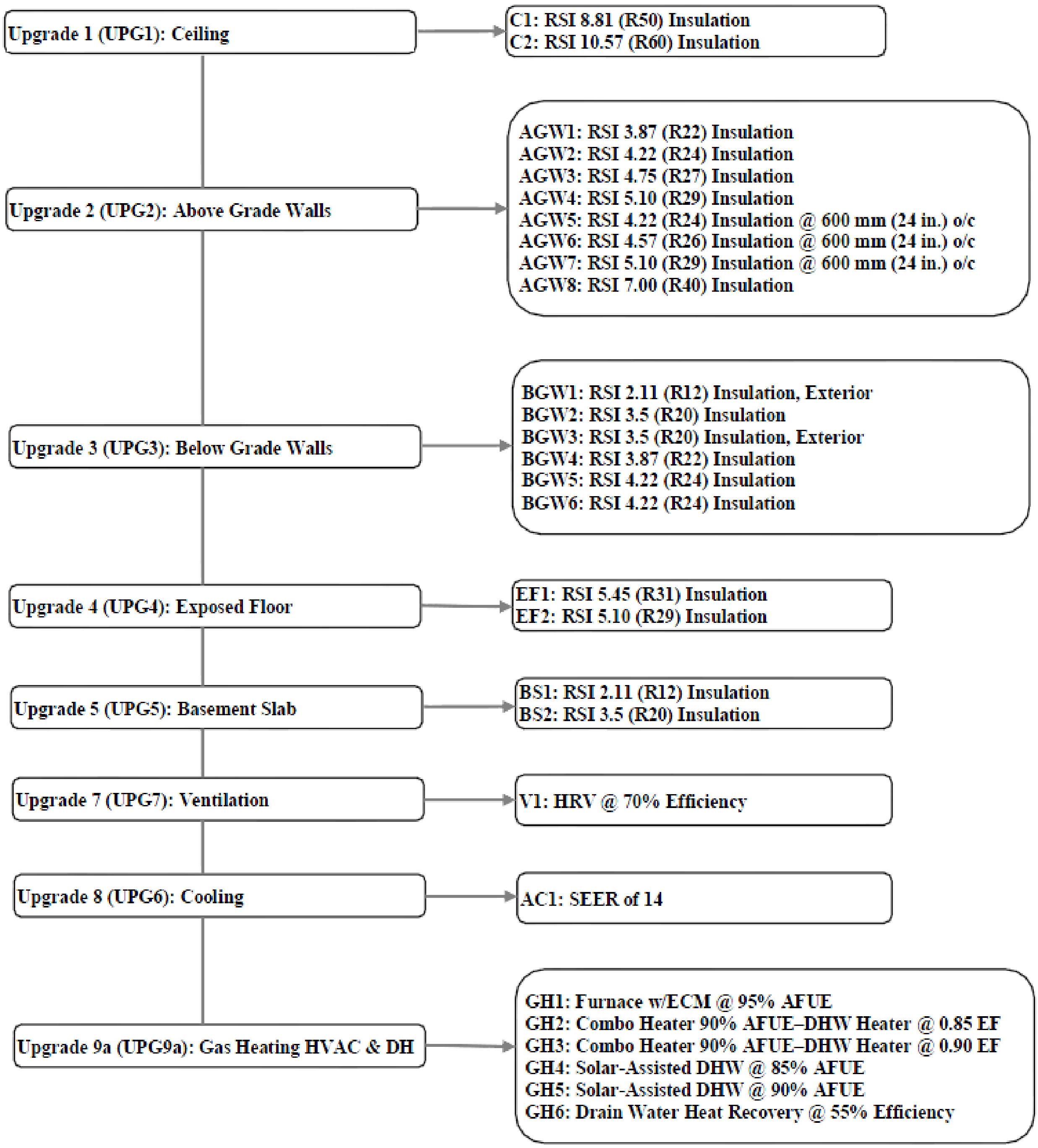


Figure 3-7: Prescribed Upgrades by Category

3.5 Cost Estimations of the Potential Least Cost Upgrades

The incremental cost of upgrades was determined based on data obtained from the "Building Construction Cost Data" (RSMeans, 2010) (Dembo, 2011) and a study done by Fung et al. (2009). The cost of each building envelope upgrade is based on the construction materials cost (RSMeans, 2010) and the total square footage of the Reference House. The incremental cost for each identified upgrade is the difference between the baseline cost and cost for the total upgrade cost (material and installation costs).

The incremental cost was based on the difference in material cost, installation cost, and overall cost of the identified upgrades against the baseline case. The baseline case was based on the Ontario Building Code (2006 OBC). The costs of the materials, installation and overall construction in the RSMeans cost data publications were based on U.S. currency. Therefore, the cost data were adjusted for a specific location in Canada, by multiplying the base cost by the "Location Factors", and then dividing by 100 (RSMeans, 2010, p. 737). Table 3-7 summarizes the location factors for Toronto, Ottawa, Thunder Bay, and Windsor in Ontario (Dembo, 2011).

Table 3-7: Location factors for different cities in Ontario (RSMeans, 2010)

Province/City	Canadian Factors (reflect Canadian currency)		
	Material Cost	Installation Cost	Total Cost
Ontario/Ottawa	121.5	90.1	107.6
Ontario/Thunder Bay	112.9	89.1	102.4
Ontario/Toronto	122.5	95.8	110.7
Ontario/Windsor	112.0	89.4	102.0

The cost estimations for HVAC systems in the residential applications were based on the last ten years of the RSMeans cost publications (Dembo, 2011). The HVAC systems in the residential applications include furnace, boiler, and an AC unit.

3.6 Life Cycle Assessment

As (Haines, et al., 2007) state, life cycle assessment (LCA) is used to evaluate the feasibility of various energy efficiency upgrade solutions, the environmental consequences and repercussions of a product, process, or activity over the span of its life. LCA methods are one of the most widely accepted tools used to compare building design options on the basis of environmental performance (Cole & Sterner, 2000). LCA is essentially a tool to not only determine the energy consumed, but ultimately the cost impact of the product in question. Any rigorous LCA requires accounting of both the costs and consumption that can lead to an energy footprint, as shown previously in Figure 2-3. However, for the building sector breaking out the specific energy footprint needs to be considered in further detail, as shown in (Haines, et al., 2007) and (Dong,et al., 2005). The detailed product from birth to death essentially entails resources which are consumed in energy, water, and raw materials for each stage of the five stages as shown in Figure 2-4, which consist of:

1) Raw material acquisition
2) Fabrication of construction materials
3) Construction activities
4) Operation and maintenance over service life
5) End of life, recycle, reuse, and (or) demolish and dispose

3.6.1 Life Cycle Cost Analysis

Ideally the full impact of the five stages of product life need to be considered in a complete LCA, but for the scope of this report only the major contributors to the building life cycle energy were considered. Figure 3-8 shows a typical LCA that was performed on the upgrades in this study. This figure represents a typical LCA for the residential heating system. The majority of costing for such systems comprises three main contributors, namely: fuel costs 68 percent, initial costs 23 percent, and maintenance costs 9 percent. It should be noted that the breakdown percentages shown here are not the same as the upgrades, however similar in breakdown.

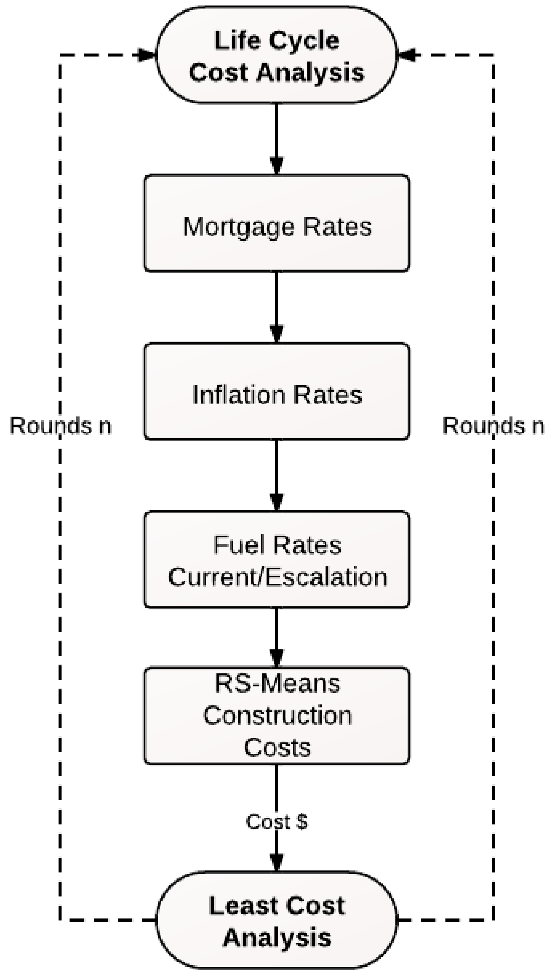


Figure 3-8: Life Cycle Cost Analysis

Based on the Dembo, 2011 study, there is an assumption that the initial costs, such as capital and installation costs for the identified upgrades will be paid at the end of the first year. As Dembo, 2011 states “Mortgage rate was used to calculate the present value of all the payments; however, assuming a real-life situation, the initial costs were spread over the mortgage period, and discount rate was used for the present value calculations. Hence, the incremental costs, therefore, had to be spread over the mortgage period using mortgage rate, and then, brought to the present value using discount rate. This methodology was applied for the calculation of the initial costs of the upgrades”. (p.73)

(Dembo, 2011) also noted that “for those upgrades that had a life expectancy of less than the identified mortgage period of 30 years, in this case the HVAC system upgrades, additional costs that occurred at a later point in the identified life span were treated as one-time expenses” (p.73).

Figure 3-9 shows a typical cash flow diagram for total AC system Life Cycle Assessment, over the life cycle of 30 years.

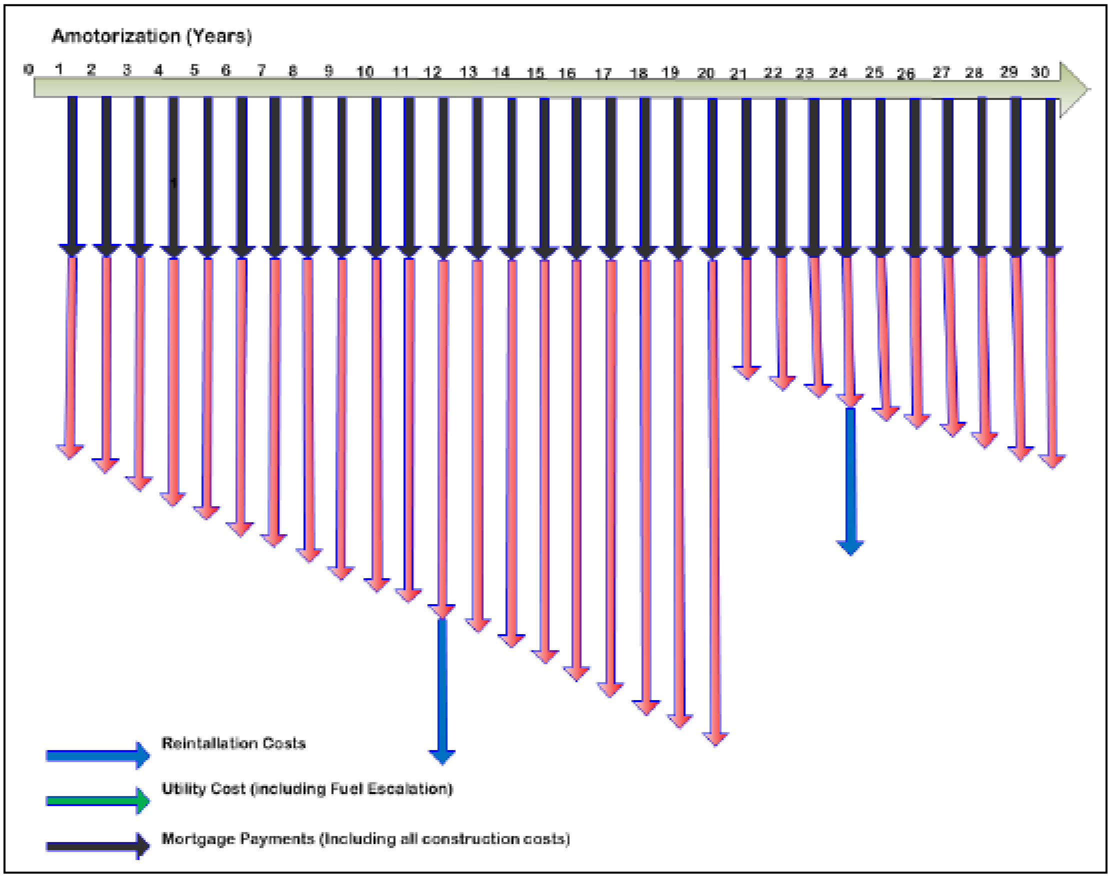


Figure 3-9: Typical Cash Flow Diagram for Total AC System Life Cycle Assessment

The assessment (Dembo, 2011) took into account the following factors which were direct contributors to the resulting building energy consumption and costs associated with each prescriptive upgrade. It should be noted that these values were assumed constant for current financial and market conditions and any major changes to these can affect the outcome of the LCU.

3.6.2 Mortgage rate

Mortgage rate was used to calculate the Net Present Value (NPV) of all payments. Initial costs were spread over the amortization period. Mortgage rate was determined based on the historical mortgage rate for a five-year term (Statistics Canada, 2011). Based on the statistics, it was assumed that mortgage rate was at the lowest value in 2009 at 5.05%, Figure 3-10 (Dembo, 2011).

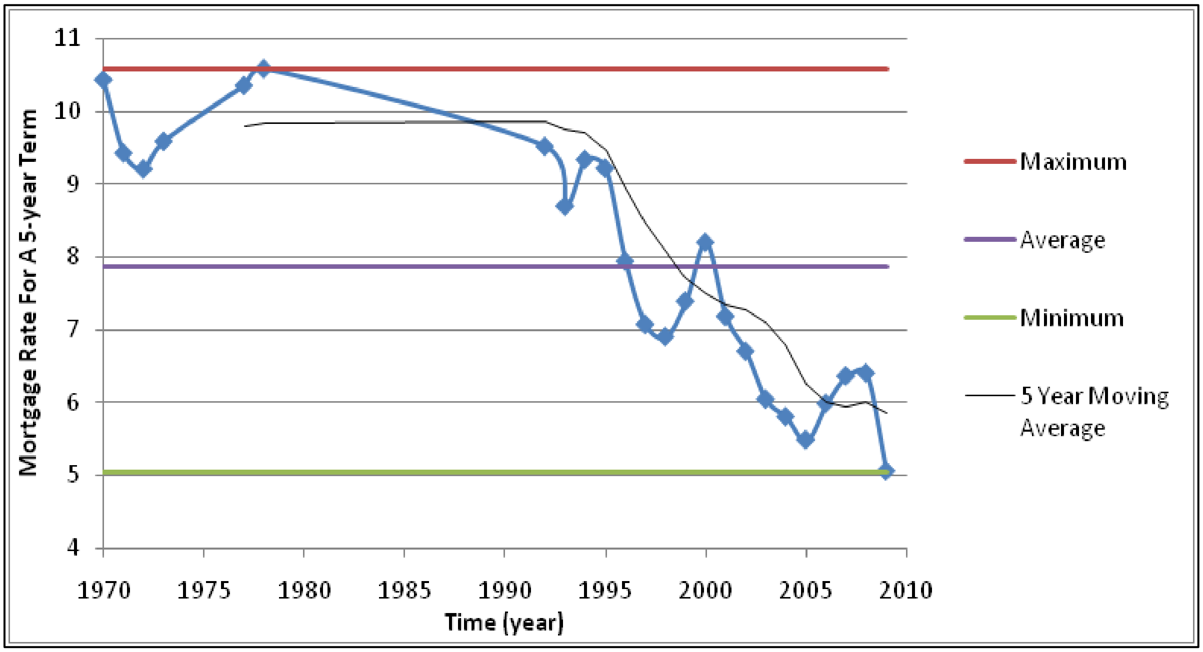


Figure 3-10: Canadian Mortgage Rates (1907 – 2008) (Dembo, 2011, p.75)

As a result, 5.05%, 7.87%, and 10.59% were used as minimum, average, and maximum mortgage rates in the proposed methodology, respectively (Dembo, 2011).

3.6.3 Discount rate

Discount rate used to calculate the Net Present Value (NPV) of all payments. Initial costs were spread over the amortization period. The rates were derived based on historical discount rates from 1995 to 2009 for Ontario, Canada (Ontario Ministry of Finance [OMF], 2010). Based on the statistics, shown in Figure 3-11, the average discount rate was determined to be 1.99%, which was based on the determination of minimum and maximum discount rates of 0.40% and 3.10%, respectively, and used as the identified discount rate for further calculations (Dembo, 2011).

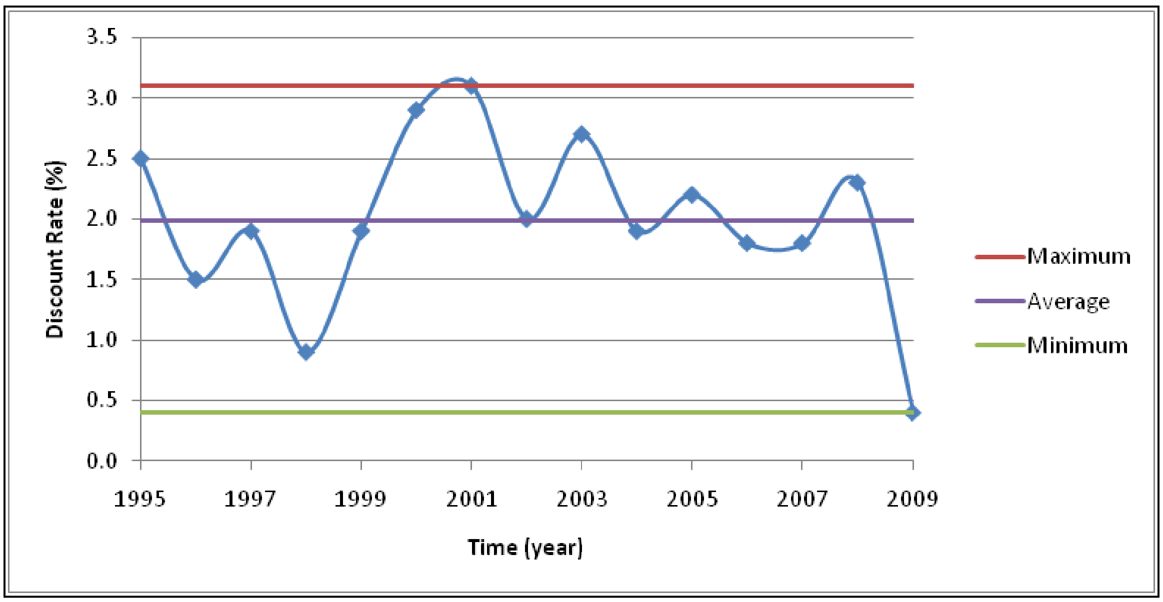


Figure 3-11: Discount rate vs. time (Dembo, 2011, p.76)

3.6.4 Electricity price escalation rates

The Consumer Price Index (CPI) for electricity and gas is an indicator of change in prices over a reference base period. At present, the reference year is 2002 (Statistics Canada, 2011). The average percent change of electricity price was determined to be 2.92%, as shown in Figure 3-12; thus, the average percent change of CPI from 1990 to 2008 gas was 4.92% (Statistics Canada, 2011 as reported in Dembo, 2011), as shown in Figure 3-13.

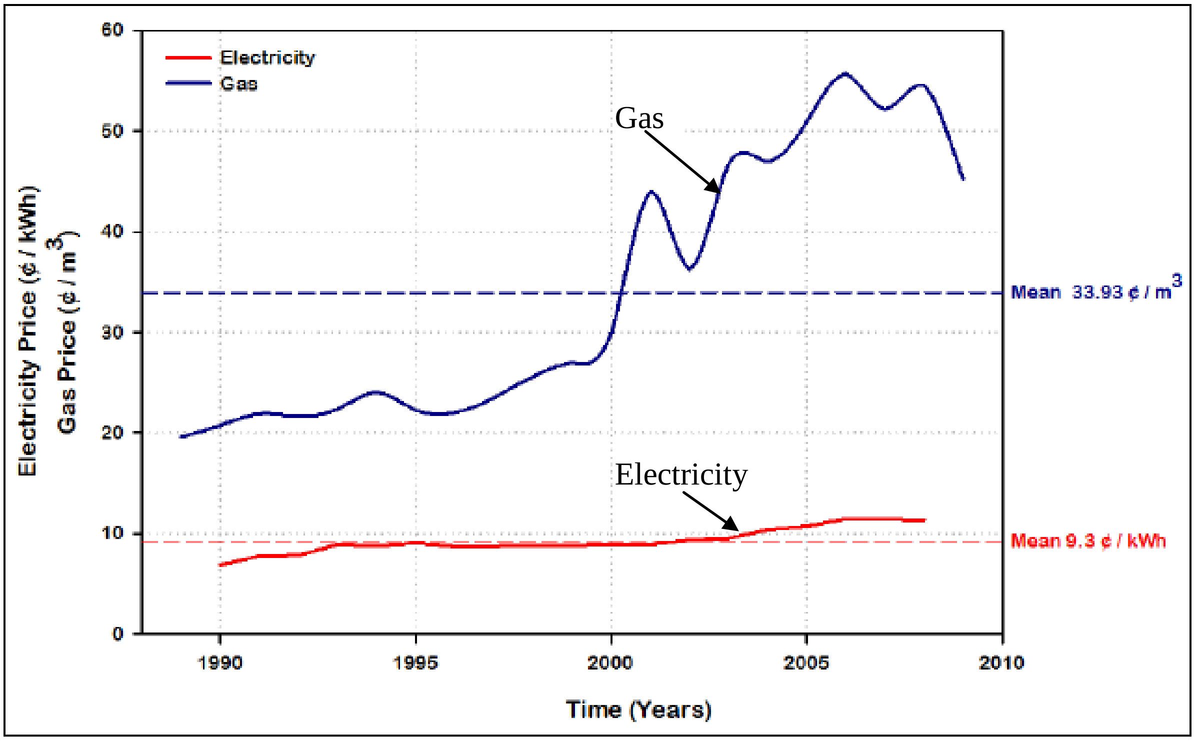


Figure 3-12: Ontario Historical Electricity & Gas Prices (OEB, 2011)

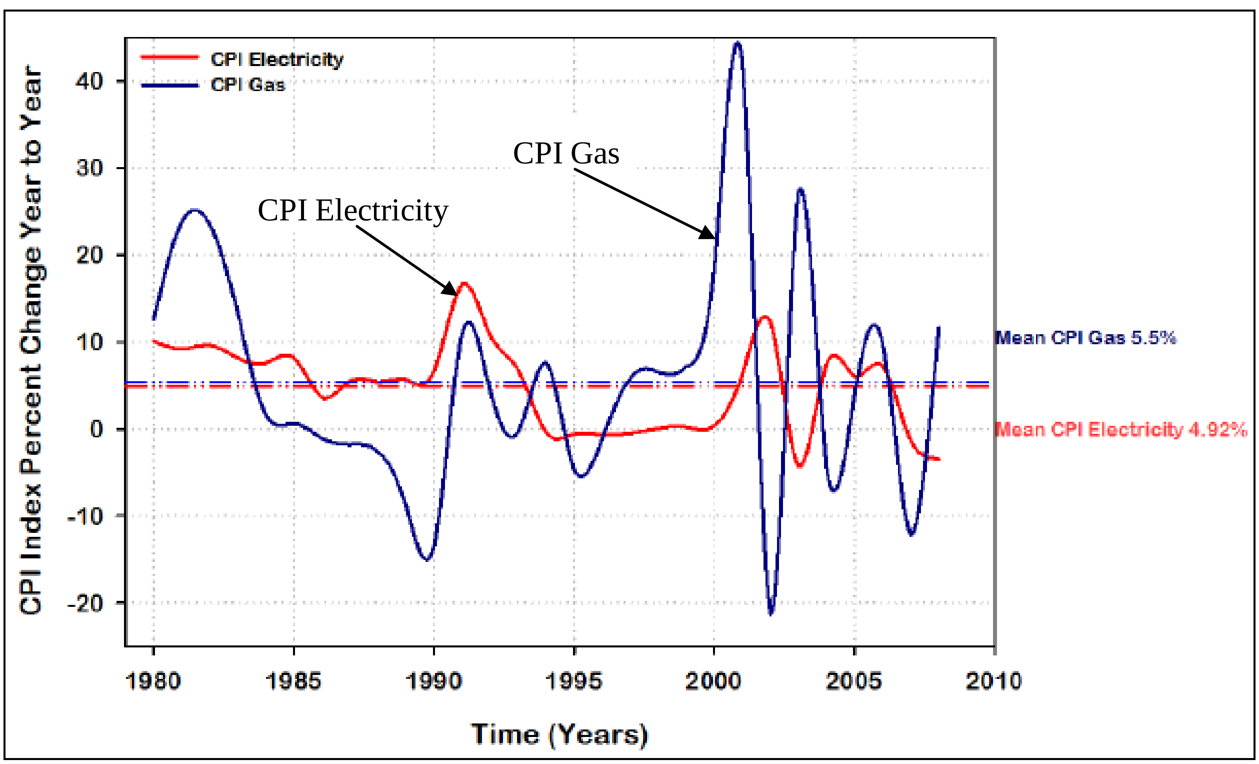


Figure 3-13: Ontario Consumer Price Index – Gas & Electricity (Statistics Canada, 2011)

"In addition to the historical prices, the electricity price forecast was obtained, based on the predicted future electricity price from 2000 to 2030, was determined to be 4.16% "(Dembo, 2011, p.77) as shown in Figure 3-14.

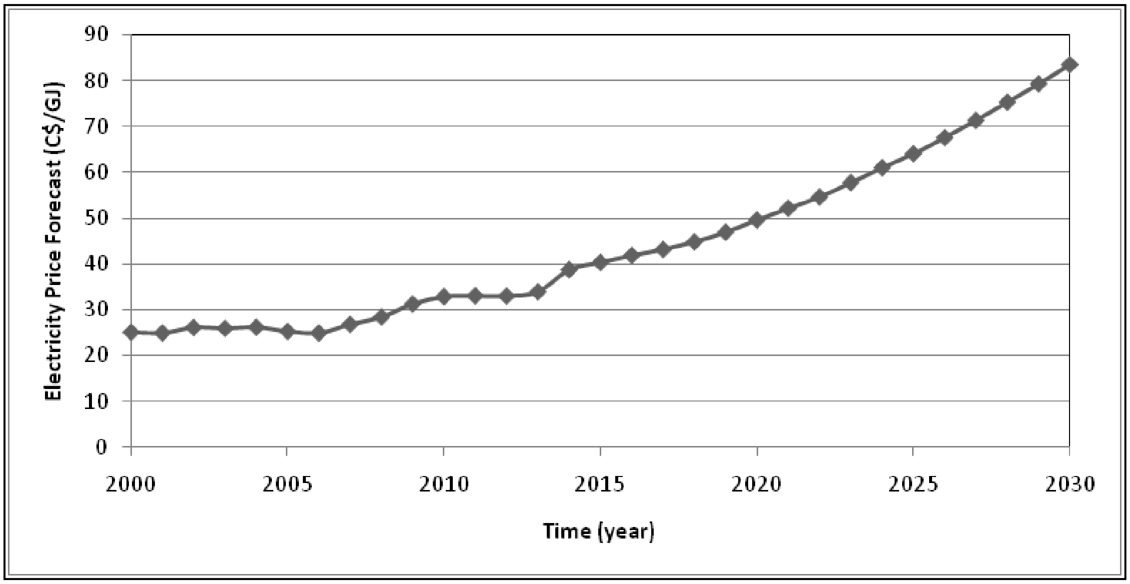


Figure 3-14: Electricity Price Forecast vs. Time (Dembo, 2011, p.77)

"The Ontario Ministry of Energy [OME] recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). In order to apply this expected increase in the future price of electricity for Ontario, the 3.50% will be used as the identified electricity price escalation rate for the proposed methodology" (Dembo, 2011, p.78).

3.6.5 Natural gas price escalation rates

As stated previously for electricity, the change in CPI for natural gas is in the same fashion. Based on the historical natural gas prices from 1990 to 2008 (Statistics Canada, 2010), the average percent change of natural gas price was determined to be 5.11% (Dembo, 2011), as shown in Figure 3-12. In addition to the historical prices, the natural gas price forecast was obtained from 2000 to 2030 to be 3.02% (Statistics Canada, 2010).

The CPI for natural gas was also considered. It should be noted, the CPI does not provide the prices paid by the consumer; however, it provides a useful indication of the changes in prices with reference to the official base period, which, at present, is the year 2002 (Statistics Canada, 2011). Therefore, the average percent change of CPI for natural gas from 1990 to 2008 was determined to be 5.50% (Dembo, 2011) as shown in Figure 3-13.

3.7 Sensitivity Analysis Parameters

Least cost upgrades as discussed are a function of many variables and economic parameters (discount rate, mortgage rate, electricity rate, natural gas rate, tax rate, amortization period, and fuel costs (gas & electricity)). In the previous sections, a set of economic parameters was determined based on the data obtained from various sources. The effect of these variables on the resulting upgrades needs to be considered. Three cases will be examined here: an average (Case 1), 2006 gas costs (Case 2a), and 2008 gas costs (Case 2b), in order to see the effects of the change these variables, which have been summarized in Table 3-8. A similar study was also performed by (Dembo, 2011), using the HOT2000 software. A comparison with those results will also be shown.

Case 1: Average Parameters

Averages of all the economic parameters are listed in Table 3-8. Data shows the historical averages for the economic and fuel parameters. The identified parameters were as follows: 30-year mortgage at a 7.87% mortgage rate (average) with 1.99% inflation rate (average). The fuel price escalation rates for electricity (average) is 3.50% and for natural gas (average) is 3.02%. The commodity pricing (Dembo, 2011) of both utilities are listed in Table 3-8.

Case 2a: 2006 Gas Fuel Costs

For this case, the identified parameters were changed as follows: 30-year mortgage (same as the previous case) at a 5.05% mortgage rate (minimum) with 3.10% inflation rate (maximum). The fuel price escalation rates for electricity and natural gas, are 3.50% (same as the previous case) and 5.50% (maximum), respectively, based on natural gas using the identified commodity prices in 2006 (Case 2a) (Dembo, 2011). The prices were determined based on the historical data provided by the OEB (2008), as summarized in Table 3-8.

Case 2b: 2008 Gas Fuel Costs

For this case, the identified parameters were changed as follows: 30-year mortgage (same as the previous case) at a 5.05% mortgage rate (minimum) with 3.10% inflation rate (maximum). The fuel price escalation rates for electricity and natural gas are 3.50% (same as the previous case) and 5.50% (maximum), respectively, based on the identified commodity prices in 2008 (Case 2b) (Dembo, 2011). The prices were determined based on the historical data provided by the OEB (2008), as summarized in Table 3-8.

Table 3-8: Sensitivity Analysis Parameters for Toronto, Ontario in CAD

Toronto, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Parameters							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Inflation	%	1.99		3.10			
Mortgage	%	7.87		5.05			
Electricity Escalation	%	3.50		3.50			
Gas Escalation	%	3.02		5.50			
Tax	%	13.00					
Amortisation	Years	30					
Electricity Pricing Monthly (Includes delivery, debt, supply, transmission, before tax)							
Electricity Price	$ / kWh	0.1038					
> 800 kWh	$ / kWh	0.1138					
Natural Gas Delivery Monthly (Includes delivery, gas supply, storage charge before tax)							
Gas Provider 1	$ / m^3	0.2892		0.7053		0.5300	
Next 55 m^3	$ / m^3	0.2843		0.7053		0.5300	
Next 170 m^3	$ / m^3	0.2892		0.7053		0.5300	
Over 170 m^3	$ / m^3	0.2843		0.7053		0.5300	
Gas Provider 2	$ / m^3	0.2892		0.7152		0.5379	
Next 150 m^3	$ / m^3	0.2843		0.7152		0.5379	
Next 250 m^3	$ / m^3	0.2892		0.7152		0.5379	

Note: Rates taken from Toronto Hydro Electric System, Enbridge, & Union Gas, Ontario Energy Board
[1] The OME recently announced the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.

[2] The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).

3.8 Least Cost Upgrade (LCU)

Many optimization techniques exist from the easiest brute force sequential search to the sophisticated multi-objective Genetic Algorithm (GA) method. In this work, it is proposed that the basic brute force sequential search be used because of its ease of implementation if the number of scenarios to be evaluated is limited and only single objective in this case, overall cost and energy consumption is to be optimized. Previous studies have employed similar algorithms to determine the least cost of potential upgrades (Gorgolewshi, et al.; Gorgolewski, 1995). To achieve the objective stated above; the following steps/procedures will be considered:

1) Determination of cost for each selected upgrade case
2) Determination of energy consumption for each case
3) Using a brute force sequential search method to determine the move cost effective upgrade by consumption and cost for first round 1
4) Repeating the previous step, whilst holding the most cost effective upgrade to the subsequent rounds, until all upgrade cases have been exhausted

Figure 3-15 shows a typical BFSS method for a series of upgrades. From Round 1, the GH6 upgrade is selected and updated in the simulation model, carrying through to Round 2 where the AC1 upgrade is selected. The sequence is carried from round to round, until an optimal model is created based upon the collection of each upgrade per round. The final model with all desired upgrades is denoted the optimal least cost model.

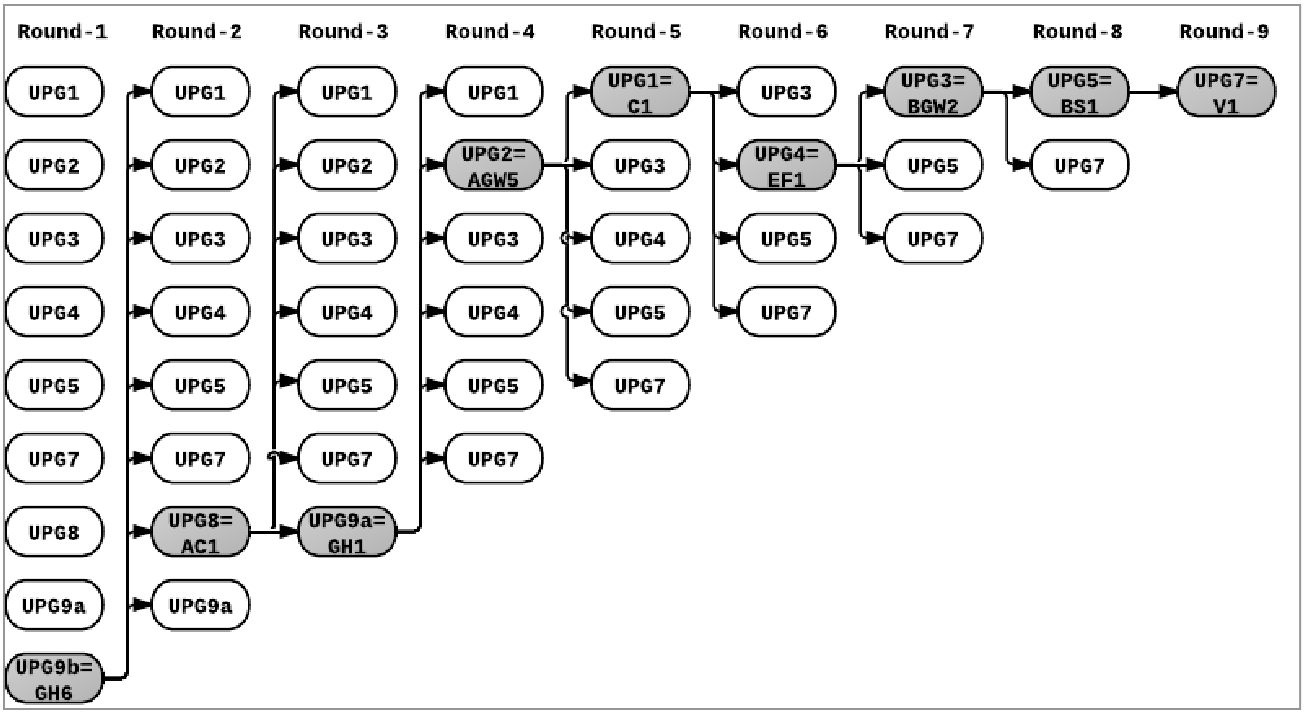


Figure 3-15: Least Cost Analysis using Brute Force Sequential Search (BFSS)

Chapter 4

4 Analyses

4.1 Overview

For innovative building energy technologies to be viable over conventional or current construction practices, they must demonstrate that they can cost-effectively increase the overall product value and quality, whilst reducing energy use (Anderson & Christensen, 2006). The objectives of this research were as follows:

1) Developing a method for determining least cost upgrades in residential housing.
2) Integrating these energy efficient upgrades into a reference CCHT house that will reduce consumption while minimizing initial costs.

To evaluate the ECOs of each upgrade, both cost and energy consumption can be calculated, and through a baseline case (2006 OBC) a reference point can be determined. Once all upgrades have been evaluated against the baseline case, a brute force sequential search algorithm will be applied and optimal LCU model determined. Studies have shown (Anderson & Christensen, 2006) that the sequential search technique efficiently identifies least cost potentials of upgrades. This LCU once modeled will be benchmarked against a reference baseline case.

This section is broken into three main sections, which were the main data collection, analysis and results of the LCU study that were performed. The following steps were taken in order to complete this section

1) Upgrades and the building code
2) Life cycle cost analysis of upgrades
3) Energy model analysis of upgrades
4) Least Cost analysis of upgrades
5) Sensitivity analysis of upgrades

4.2 Upgrades and Building Code Analysis

The development of building code standards is undertaken by a consortium of interested parties in order to assure that the performance levels are economically attainable. There are several groups and research consortiums that have developed their own standards, such as NRC and ASHRAE (CCHT, 2011; CHBA, 2011; Government of Ontario, 2011; NRC, 2005). However these standards are not enforceable by law until a provincial agency adopts these standards into the building code. A case in point, currently in Ontario the 2006 OBC is the provincial standard, whereas the R2000 (CHBA, 2011) is a voluntary standard. However there is a new building code 2012 OBC which will be in place by December 31, 2011 (Government of Ontario, 2011). In this study the reference case being used is the 2006 OBC. As shown in Table 2-4, OBC building codes tend to have two standards within the code, one for gas and the other for electric heating. The 2012 OBC follows these criteria, but has put in place many options that allow HVAC systems without green components such as Heat Recovery Ventilators (HRV). These comparisons help to determine the viability or benchmarking of a potential upgrade in comparison to the current code. In addition to recognizing advances in the performances of various components and equipment the upgrades will help to encourage innovative energy conserving designs and strategies. It is important not to underestimate the dynamics between upgrades, cost, and consumption. The triaging of these variables introduces numerous permutations and combinations, and it is important to understand the relationship, among these variables and sub variables, which will have implications on the LCU analysis. In previous chapters, the selection of upgrades was discussed; these myriad of upgrades include changes to the building code, HVAC systems and DHW. However, in order to run the various scenarios for the upgrades and their effect on energy consumption, a strategy needed to be used in order to compare the discreet effects of each upgrade. This was done in the following way, and is shown in Table 4-1 and Table 4-2:

1) Modeling the base case for the 2006 OBC as the baseline or reference case or model.
2) Identifying the proposed upgrade and its relationship to the 2006 OBC, and making only those changes that would affect the upgrades, whilst holding all other variables constant. The changes to each upgrade case are indicated in italicized red.
3) Running each upgrade discreetly and obtaining its total cost, and energy consumption.

One note of interest; the upgrades were reflected here as a range, to minimize the size of the resulting table, if specific values are required for each upgrade (see Table 3-6). It can be shown through both of the tables that the upgrade options meet or exceed the current 2006 OBC reference case. This step was essential, as in the next section costing of each of the upgrades will be performed followed by a detailed building simulation model.

Table 4-1: 2006 Ontario Building Code vs. Prescriptive Upgrades 1 – 5

Component	Units	2006 Building Code Gas	Prescribed Upgrade Packages Round 1				
			UPG1*	UPG2*	UPG3*	UPG4*	UPG5*
Ceiling with Attic Space Minimum RSI R-Value	$(m^2 K)/W$	7.24 R41	***8.81-10.57 R50 - R60***	7.24 R41	7.24 R41	7.24 R41	7.24 R41
Ceiling without Attic Space Minimum RSI R-Value	$(m^2 K)/W$	5.21 R30	***8.81-10.57 R50 - R60***	5.21 R30	5.21 R30	5.21 R30	5.21 R30
Exposed Floor Minimum RSI R-Value	$(m^2 K)/W$	4.70 R27	4.70 R27	4.70 R27	4.70 R27	***5.10 - 5.45 R29 - R31***	4.70 R27
Walls Above Grade Minimum RSI R-Value	$(m^2 K)/W$	3.80 R22	3.80 R22	***3.87 - 7.0 R22 - R40***	3.80 R22	3.80 R22	3.80 R22
Basement Walls Minimum RSI R-Value	$(m^2 K)/W$	2.4 R14	2.4 R14	2.4 R14	***2.11 - 4.22 R12 - R50***	2.4 R14	2.4 R14
Below Grade Slab Entire Surface > 600 mm Minimum RSI R-Value	$(m^2 K)/W$	1.76 R10	1.76 R10	1.76 R10	1.76 R10	1.76 R10	***2.11 - 3.5 R12 - R20***
Edge of Below Grade Slab < 600 mm Minimum RSI R-Value	$(m^2 K)/W$	-	-	-	-	-	***2.11 - 3.5 R12 - R20***
Windows & Sliding Glass Doors Maximum U-Value	$W/(m^2 K)$	2	2	2	2	2	2
Space Heating Equipment	Minimum AFUE	90%	90%	90%	90%	90%	90%
Electric Space Heating Equipment	Minimum Efficiency	-	-	-	-	-	-
Heat Recovery Ventilator (HRV)	Minimum Efficiency	-	-	-	-	-	-
Domestic Hot Water Heater	Energy Factor	0.57 (3)	0.57 (3)	0.57 (3)	0.57 (3)	0.57 (3)	0.57 (3)
Air Conditioning Minimum	Seasonal Energy Efficiency Ratio	13	-	-	-	-	-

Note: Environment data taken from (Government of Ontario, 2011) *for OBC*, (CCHT, 2011) *for the As Built, &* (CHBA, 2011)*for the R2000 codes respectively.*

Table 4-2: 2006 Ontario Building Code vs. Prescriptive Upgrades 6-9

Component	Units	2006 Building Code Gas	Prescribed Upgrade Packages Round 1				
			UPG6*	UPG7*	UPG8*	UPG9a*(10)	UPG9b*(10)
Ceiling with Attic Space Minimum RSI R-Value	(m^2 K)/W	7.24 R41	7.24 R41	7.24 R41	7.24 R41	7.24 R41	7.24 R41
Ceiling without Attic Space Minimum RSI R-Value	(m^2 K)/W	5.21 R30	5.21 R30	5.21 R30	5.21 R30	5.21 R30	5.21 R30
Exposed Floor Minimum RSI R-Value	(m^2 K)/W	4.70 R27	4.70 R27	4.70 R27	4.70 R27	4.70 R27	4.70 R27
Walls Above Grade Minimum RSI R-Value	(m^2 K)/W	3.80 R22	3.80 R22	3.80 R22	3.80 R22	3.80 R22	3.80 R22
Basement Walls Minimum RSI R-Value	(m^2 K)/W	2.4 R14	2.4 R14	2.4 R14	2.4 R14	2.4 R14	2.4 R14
Below Grade Slab Entire Surface > 600 mm Minimum RSI R-Value	(m^2 K)/W	1.76 R10	1.76 R10	1.76 R10	1.76 R10	1.76 R10	1.76 R10
Edge of Below Grade Slab < 600 mm Minimum RSI R-Value	(m^2 K)/W	-	-	-	-	-	-
Windows & Sliding Glass Doors Maximum U-Value	W/(m^2 K)	2	2	2	2	2	2
Space Heating Equipment	Minimum AFUE	90%	90%	90%	90%	***95%***	
Electric Space Heating Equipment	Minimum Efficiency	-	-	-	-	-	-
Heat Recovery Ventilator (HRV)	Minimum Efficiency	-	-	***70%***	-	-	-
Domestic Hot Water Heater	Energy Factor	0.57 (3)	0.57 (3)	0.57 (3)	0.57 (3)	***0.85 – 0.90***	***1***
Air Conditioning Minimum	Seasonal Energy Efficiency Ratio	13	-	-	***14 SEER***	-	-

Note: Environment data taken from (Government of Ontario, 2011) *for OBC*, (CCHT, 2011) *for the As Built, &* (CHBA, 2011)*for the R2000 codes respectively.*

4.3 Life Cycle Assessment Analysis (LCAA)

Initial costs of all upgrades will exceed the baseline reference case. However the LCAA which was preformed incorporated all major initial costs, fuel costs, replacement cost and such illustrated in the previous section. Once costing was determined over the amortization period, the net present value (NPV) was determined to relate the cost back to today's cost. As originally predicted, all costs were above the baseline case. It is important to note that there is no direct correlation between increasing cost and efficiency of upgrades. This can be seen in upgrades AGW5, BGW2, EF2, and GH6, as these upgrades are not the highest cost; however their efficiency per dollar spent is high. These upgrades will be considered as candidates for LCU as the analysis progresses. Table 4-3 is a summary of the LCCA that was performed on the CCHT home. The following items should be noted:

1) Incremental costs were the costs over the amortization period, including all costs mentioned in Figure 3-8. All costs are in Canadian Dollars (CAD).
2) Costing for the data was done using RMS Means construction data (Construction Publishers & Consultants, 2010)
3) NPV of the baseline case with Case 1 (average economic parameters) is $93,343.
4) Incremental cost of the maximum cost was for the above grade upgrade (AGW8) (Item 10) is $20,367. The high incremental costs were due to structural changes in framing, material and labor that would result from this upgrade.

Table 4-3: Life Cycle Cost Analysis on Upgrades by Upgrade Category – Toronto, Ontario

Round 1	Upgrade	Incremental Cost	Total NPV Cost Case 1
Item	Acronym	$ CAD	$ CAD
Base (Ref)	Base	-	$93,343
Case 1	C-1	-	$108,403
1	C1	$552	$94,435
2	C2	$1,397	$96,244
3	AGW1	$1,321	$96,160
4	AGW2	$721	$94,270
5	AGW3	$4,161	$101,344
6	AGW4	$4,978	$102,809
7	AGW5	$721	$94,251
8	AGW6	$4,055	$101,331
9	AGW7	$4,872	$102,570
10	AGW8	$20,367	$136,173
11	BGW2	$1,681	$96,927
12	BGW3	$3,328	$100,636
13	BGW4	$4,375	$102,970
14	BGW5	$4,376	$102,927
15	BGW6	$12,245	$120,684
16	EF1	$394	$94,863
17	EF2	$754	$94,911
18	BS1	$1,694	$96,979
19	BS2	$3,295	$100,242
20	V1	$835	$96,934
21	AC1	$65	$93,441
22	GH1	$472	$93,594
23	GH2	$1,030	$93,983
24	GH3	$1,280	$94,459
25	GH4	$3,453	$101,309
26	GH5	$4,646	$101,230
27	GH6	$968	$93,145

4.4 Modeling Analysis

Calibrated simulation requires a systematic approach that includes the development of the entire building simulation modeling methodology as shown in Section 3.4. The calibration process involves the comparison of selected simulation data against measured data from the system being simulated and then adjusts the simulation model to improve the comparison of the simulated output against the corresponding measurement. In the case of the study, the base case was the 2006 OBC. Table 4-4 shows the energy consumption of all simulations that were run. It is important to note that the tables were broken as per the three cases, Case 1, Case 2a, & Case 2b, representing the various cases of the economic parameters previously discussed. The results have also been summarized in their totality in Table A-1(Appendix A). Some notes of interest are:

1) Fuel sources for upgrades were either gas (m^3) or electricity (kWh). For comparison purposes the total loads were calculated in kWh.
2) Building loads: Heating and cooling loads were separated and summed in the last column as the heating load is the major energy consuming load of the structure.
3) Water Loads: Domestic water heating was the second highest load in the home after heating. This is consistent with expectation (Turner & Doty, 2007), and is reflected in the table.
4) 2006 OBC Base Case: Modified to include all 2006 OBC criteria as shown in Table 2-4 to become the reference model for all further studies. This is the *"Base Reference Case"* indicated by upgrade label A in all subsequent tables.
5) Appliances / Lighting: The appliances and lighting assumptions considered in this study were based on the standard operating conditions (Urgursal & Fung, 1996) used in the CCHT reference model, which assumed that the occupancy of two adults and two children was present 50% of the time, and using 24 kWh (81,891 Btu) per day or 8,760 kWh per year of electricity consumption for appliances and lighting (NRCan, 2006). In addition, sensitivity analysis of the identified appliances and lighting assumptions was conducted to evaluate the effectiveness of the proposed upgrades by reducing electricity consumption for appliances and lighting.

The base reference case or the 2006 OBC case had a total consumption of 41,183 kWh. For all other upgrades all loads fell below the base reference case, with item GH5 (Solar DHW) showing the least consumption at 34,851 kWh. A summary of total consumption loads for each upgrade for round one, base case and optimal cases 1, 2a, and 2b are provided in Figure 4-1, with the data summarized in Table 4-4. The highest loads in the building are the gas loads (HVAC and DHW loads), followed by the heating load (HVAC), electrical loads (appliances, lighting, furnace fan, HRV fan, and exhaust fan), DHW loads, and cooling loads (AC). The base reference case has the highest loads in all categories, followed by each upgrade by round. The lowest loads are from the optimal cases that are Cases 2a, 2b, and then Case 1 for all building loads with total consumption loads of 34964 kWh, 31144 kWh, and 41, 183 kWh, respectively. Figure 4-2 shows the total consumption versus time as modeled inside TRNSYS for the baseline, Case 1, Case 2a, and Case 2b. It should be noted that Case 2a and Case 2b yielded the same final upgrades, thus having very similar plots.

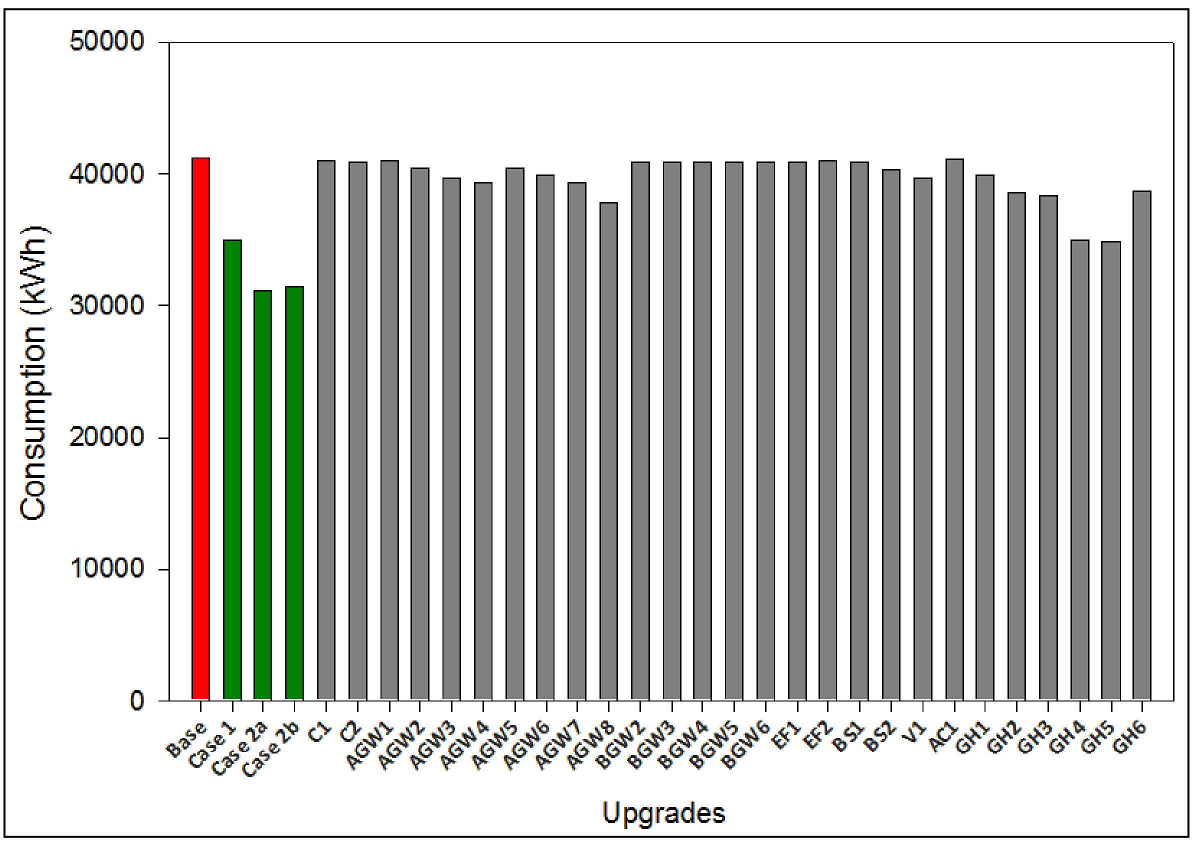


Figure 4-1: Consumption Curves All Cases and Round 1 Upgrade for Toronto, Ontario

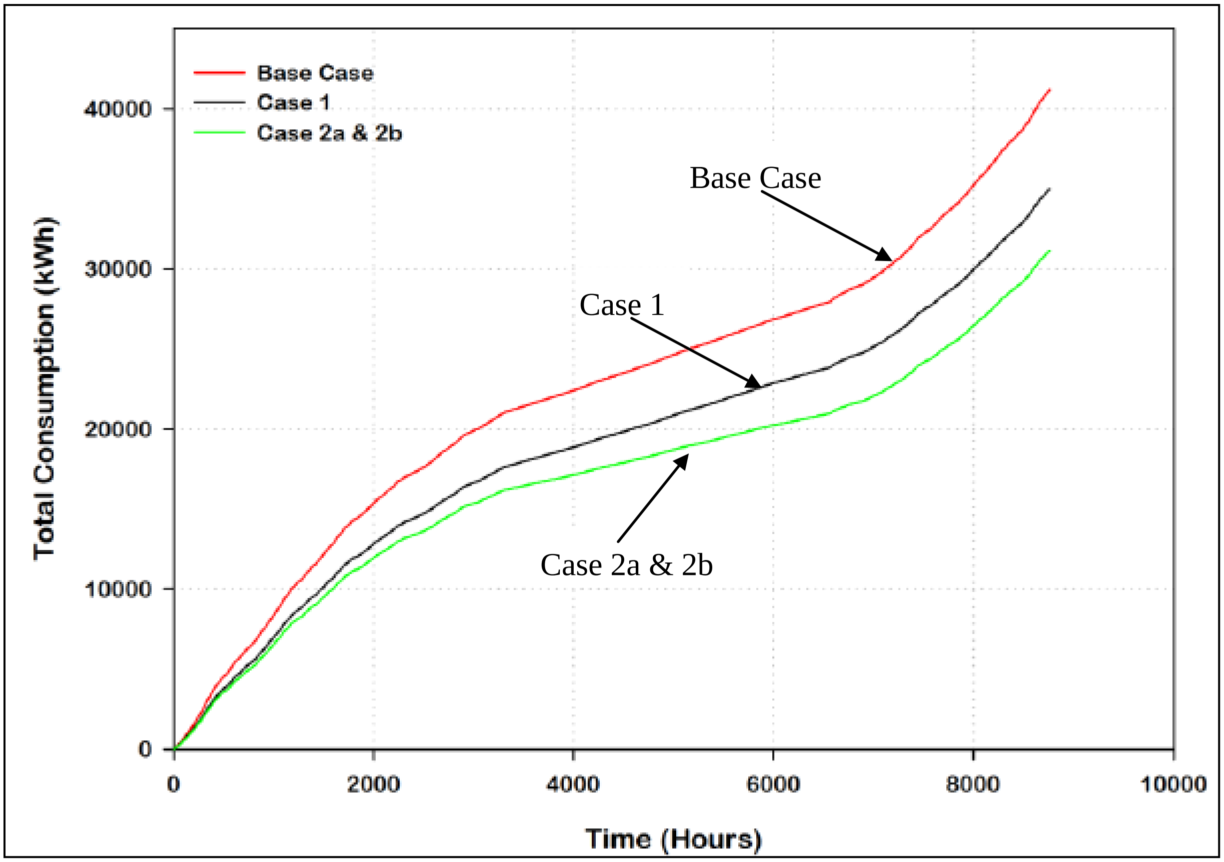


Figure 4-2: Total Consumption vs. Time Case 1, Case 2a & 2b

Table 4-4: Consumption Data All Cases and Round 1 Upgrades – Toronto, Ontario

Upgrade	Heating Load	Cooling Load	Exhaust Fan	Furnace Fan	HRV	DHW	App / Lights	Total Eclectic	Total Gas	Total
Item	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	m^3	kWh
Base	23087	707	324	570		7735	8760	10361	2908	41183
Case 1	18666	692	324	485	762	5276	8760	11023	2259	34964
Case 2a	18727	682	324	486	762	1403	8760	11014	1899	31144
Case 2b	18727	682	324	474	762	1403	8760	11290	1899	31420
C1	22929	712	324	565		7735	8760	10361	2893	41025
C2	22820	716	324	563		7735	8760	10362	2883	40917
AGW1	22913	713	324	565		7735	8760	10362	2891	41010
AGW2	22345	730	324	551		7735	8760	10365	2838	40445
AGW3	21625	750	324	533		7735	8760	10367	2770	39727
AGW4	21221	763	324	523		7735	8760	10370	2732	39325
AGW5	22330	730	324	550		7735	8760	10364	2836	40429
AGW6	21861	744	324	539		7735	8760	10367	2792	39962
AGW7	21221	763	324	523		7735	8760	10370	2732	39325
AGW8	19768	809	324	487		7735	8760	10380	2595	37883
BGW2	22836	721	324	563		7735	8760	10368	2884	40939
BGW3	22831	721	324	563		7735	8760	10368	2884	40934
BGW4	22787	725	324	562		7735	8760	10370	2879	40892
BGW5	22744	725	324	561		7735	8760	10370	2875	40849
BGW6	22744	725	324	561		7735	8760	10370	2875	40849
EF1	22804	735	324	562		7735	8760	10381	2881	40920
EF2	22904	721	324	565		7735	8760	10370	2890	41009
BS1	22802	734	324	562		7735	8760	10380	2881	40917
BS2	22222	793	324	548		7735	8760	10425	2826	40382
V1	20998	655	324	516	762	7735	8760	11017	2711	39749
AC1	23050	684	324	568		7735	8760	10336	2904	41121
GH1	21837	709	324	568		7735	8760	10361	2790	39933
GH2	23087	707	324	570		5187	8760	10361	2667	38635
GH3	23087	707	324	570		4899	8760	10361	2640	38347
GH4	23087	707	324	570		1485	8760	10361	2318	34933
GH5	23087	707	324	570		1403	8760	10361	2310	34851
GH6	23087	707	324	570		5276	8760	10361	2676	38724

4.5 Least Cost Upgrades (LCU) Analysis

The path to least cost upgrades analysis has been an arduous one. It entailed the compilation of numerous building simulation models and economic data to drive the brute force sequential search algorithm- upgrade cost, and consumption. Using the BFSS algorithm, all upgraded incremental cost data and total consumption data from Table 4-5 yielded the most optimal upgrade by category and round. Figure 4-3, Figure 4-4, and Figure 4-5 show the typical sequence of the BFSS over each round for Case 1 and Cases 2a and 2b, respectively. Consider the first round of Case 1 as an example. The incremental cost of GH6 was $968 CAD, with total consumption of 38,724 kWh being lower than the baseline case of 41,183 kWh. However, this upgrade being a DHW category had a consumption of 5,276 kWh, which was well below the base case of 7,735 kWh. This upgrade was the most cost effective of all categories, thus winning the first round. This upgrade was then applied to the house, and carried through the second round. The BFSS at that point searched out the best upgrade for the second round, which was AC1, an air conditioning upgrade of SEER 14. The algorithm proceeded in its search through all nine rounds, which corresponded to all nine categories of upgrades (category nine has two sub categories). Ultimately the BFSS designed an optimal upgrade sequence of a house with all the optimal upgrades as shown in Figure 4-3. All results were continuously benchmarked against the 2006 OBC base reference case. It is important to note here that some of the predicted categories in the proceeding sections that were leaders in cost or consumption essentially won out each case for their specific category, ultimately ranking them the best in their class for the LCU analysis. Table 4-6 shows the cost and consumption of the cases and upgrades by category. Case 1 average case parameter had the lowest NPV at $93,343, while Case 2a yielded a cost of $152,923, and Case 2b at $128,917 when gas prices were raised. Once the upgrades were determined by category, all of these upgrades were applied to the model denoted Case 1, Case 2a, and Case 2b in all subsequent tables, also listed in Appendix A, and shown in Figure 4-3, Figure 4-4 and Figure 4-5. It is important to note here that the Case 1, Case 2a, and Case 2b models fell well below the baseline reference case in consumption as shown in Figure 4-6, Figure 4-7 and Figure 4-8. Final efficiencies from the base case were 18%, 32% and 31% for Cases 1, 2a, and 2b, respectively, as shown in Table 4-8. The choice of upgrades were essentially the same among the three cases, only with a major change in sequence and the initial DHW upgrades being GH6 drain water recovery, and GH5 a solar assisted DHW option, that cost $968 and $4646 respectively. The following items are important to consider here.

1) NPV of the base case was $93,343, $152,923, and $128,917 for Case 1, Case 2a, and Case 2b.
2) NPV of the optimal cases were $108,403, $142,804, and $128,219 for Case 1, Case 2a, and Case 2b, respectively.
3) Taking the difference of the base and optimal cost, the initial NPV of the all upgrades for each case is shown to be $15,060, -$10,119, and -$698 for Case 1, Case 2a, and Case 2b, respectively. It is interesting to note that in cases 2a and 2b there was actually a reduced NPV cost of implementing the upgrades whilst Case 1 required an additional $15,060 to pay for the extra upgrades.

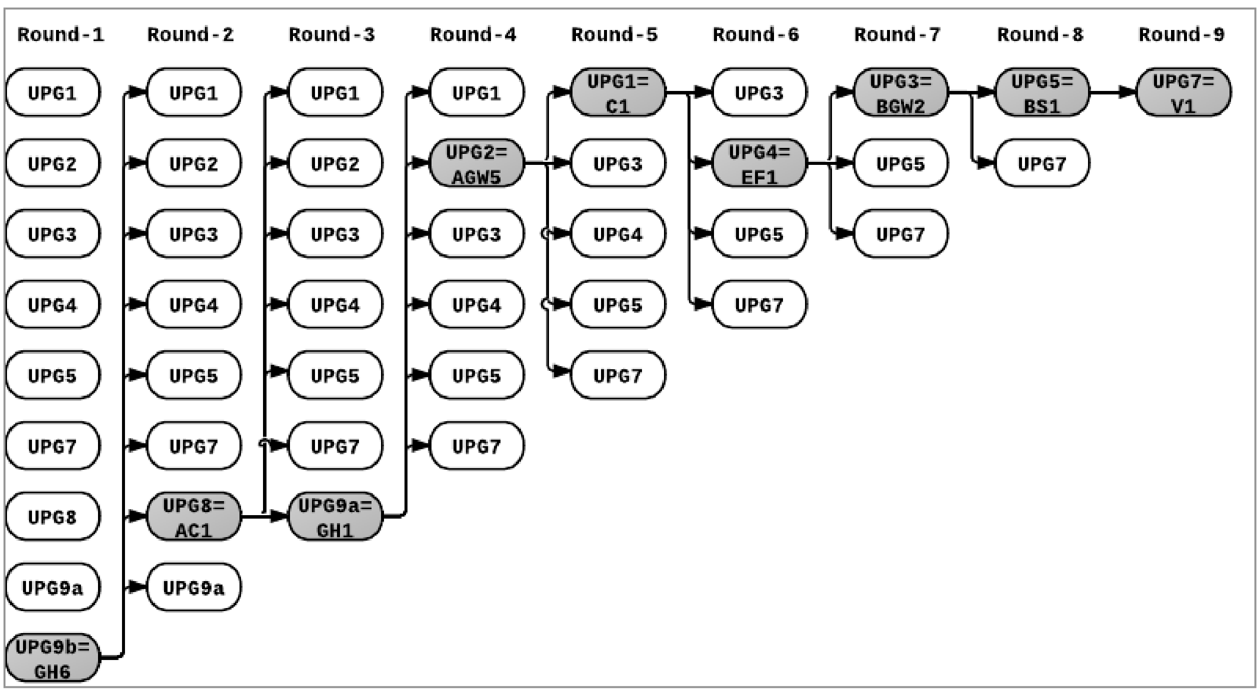


Figure 4-3: Brute Force Sequential Search Method (BFSSM) Case 1

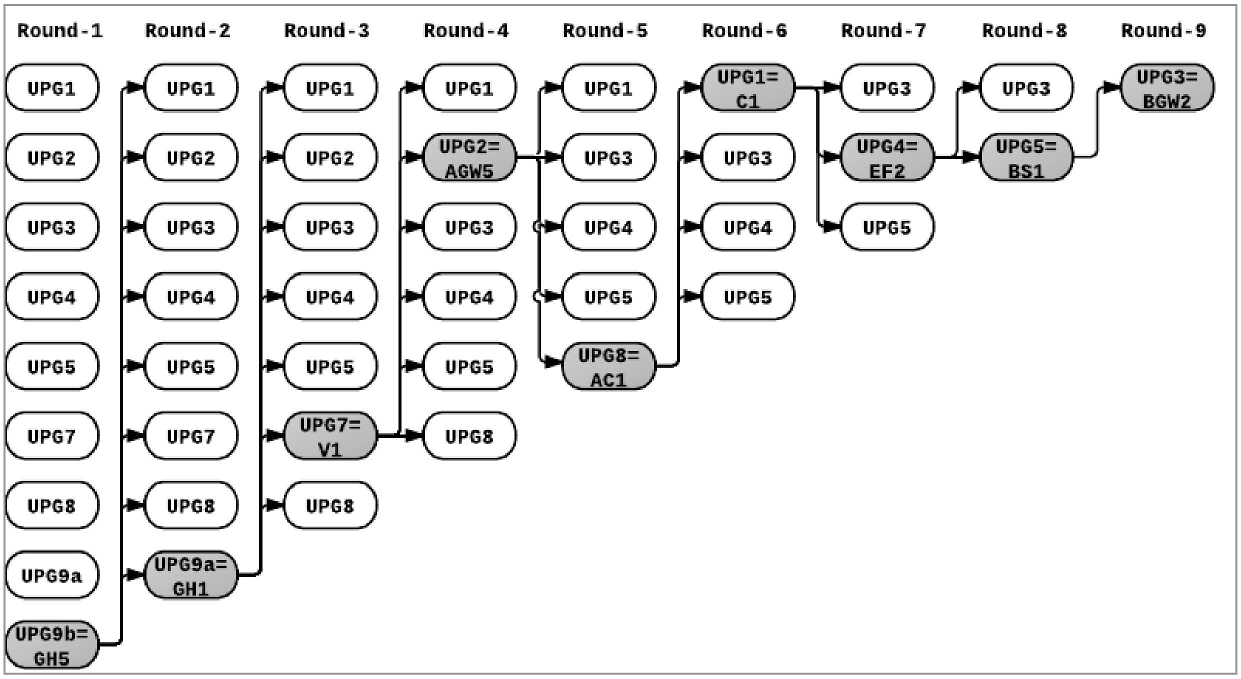


Figure 4-4: Brute Force Sequential Search Method (BFSSM) Case 2a

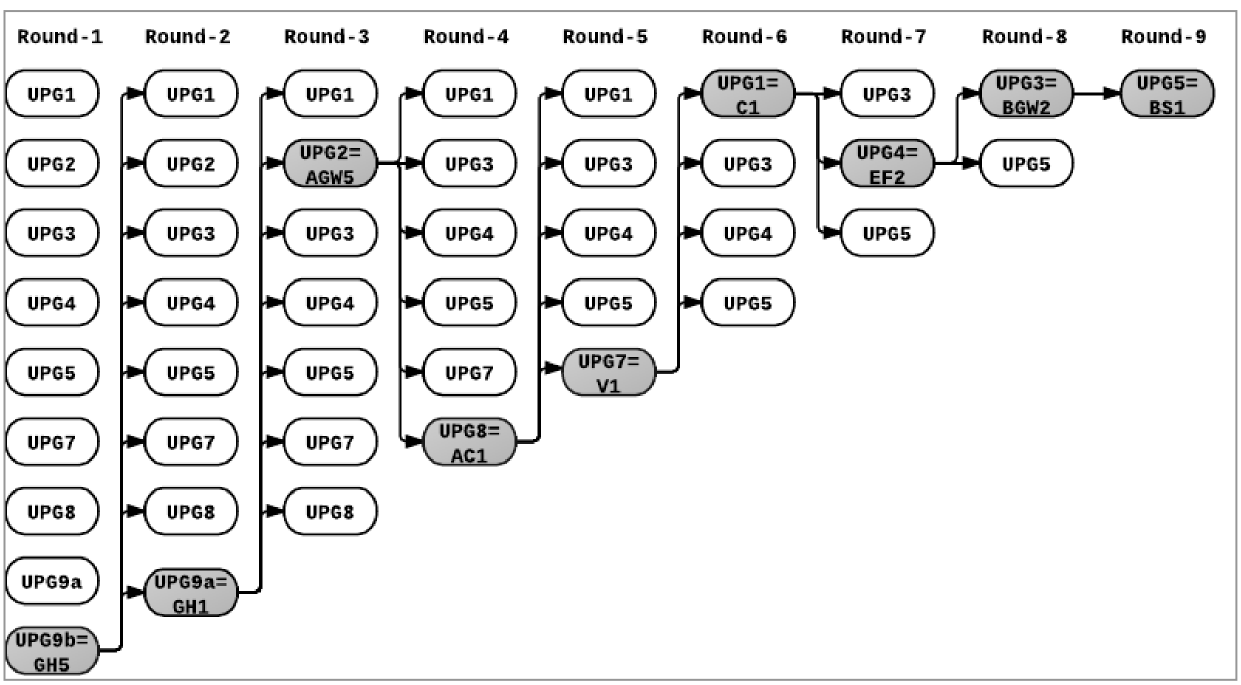


Figure 4-5: Brute Force Sequential Search Method (BFSSM) Case 2b

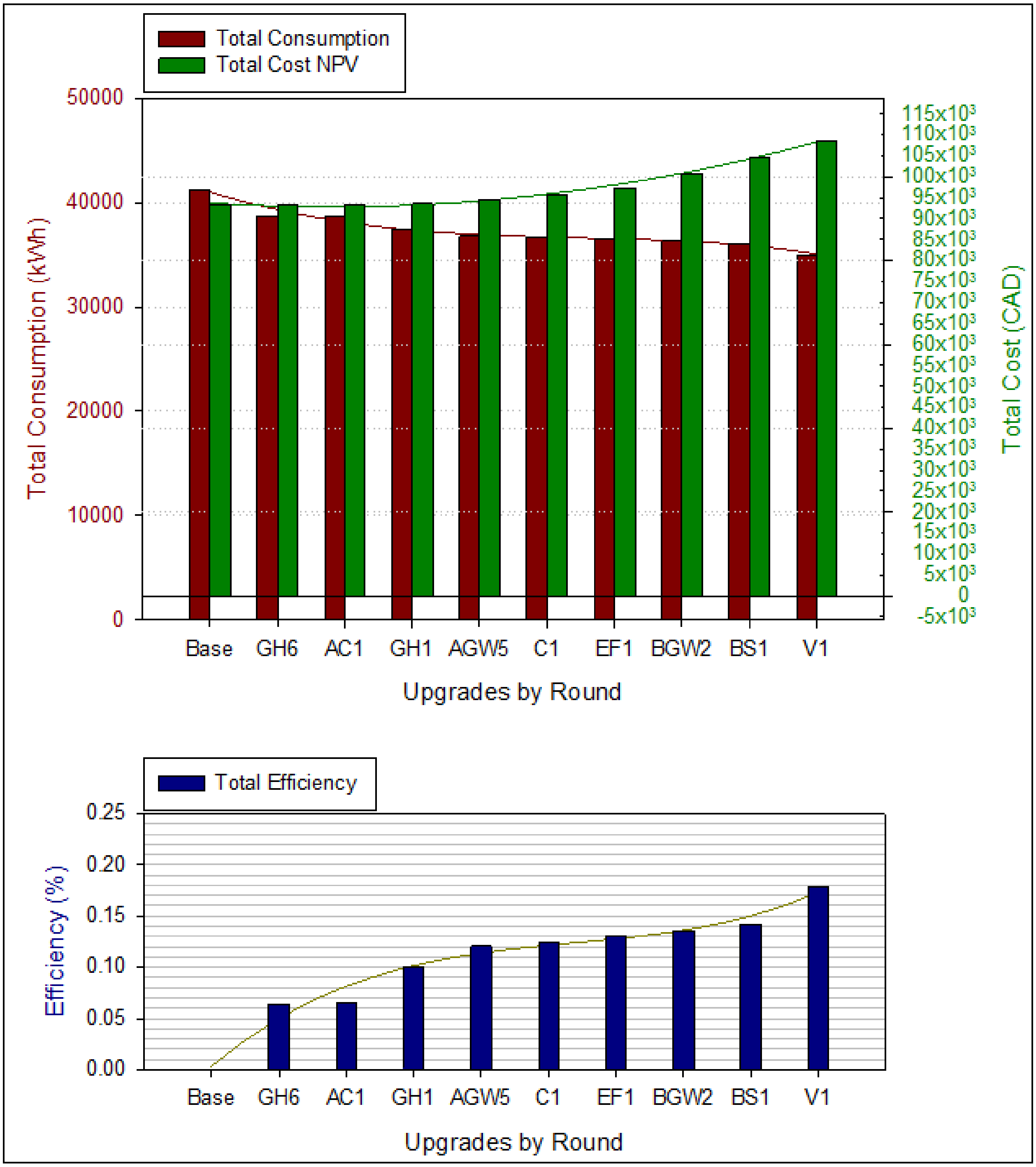


Figure 4-6: Total Consumption, NPV Cost, and Efficiency by Round Case 1

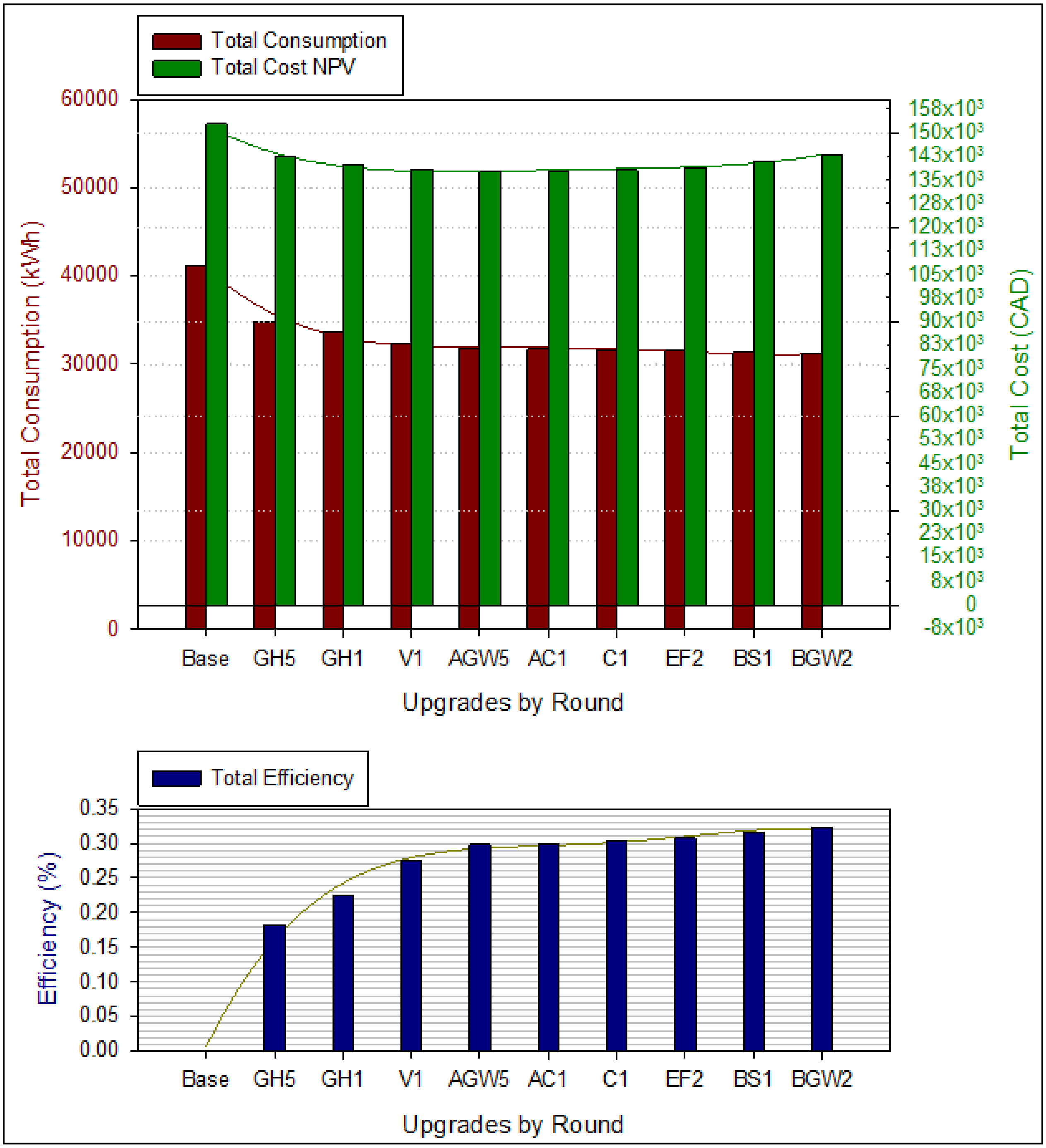


Figure 4-7: Total Consumption & NPV Cost, and Efficiency by Round Case 2a

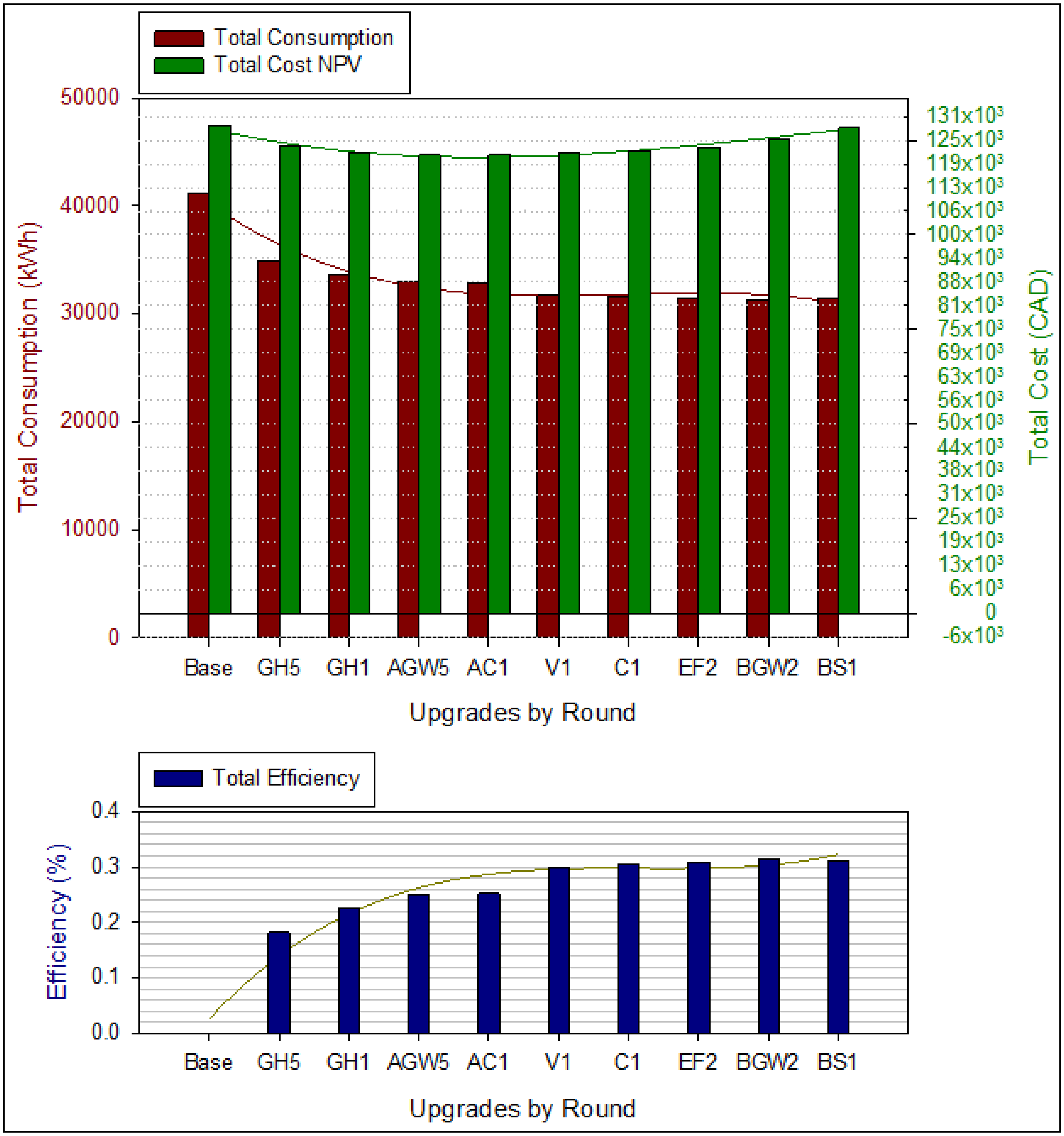


Figure 4-8: Total Consumption, NPV Cost, and Efficiency by Round Case 2b

Table 4-5: Least Cost Analysis Prescription Upgrades Case 1

Component	Units	As Built	Base Case	Case 1
Ceiling with Attic Space Minimum RSI R-Value	$(m^2 K)/W$	8.6 (R49)	7.24 (R41)	C1 (R50)
Exposed Floor Minimum RSI R-Value	$(m^2 K)/W$	4.4 (R25)	4.70 (R27)	EF1 (R29)
Walls Above Grade Minimum RSI R-Value	$(m^2 K)/W$	3.5 (R20)	3.80 (R22)	AGW5 (R24)
Basement Walls Minimum RSI R-Value	$(m^2 K)/W$	3.5 (R20)	2.4 (R14)	BGW2 (R20)
Below Grade Slab Entire Surface > 600 mm Minimum RSI R-Value	$(m^2 K)/W$		1.76 (R10)	BS1 (R12)
Windows & Sliding Glass Doors Maximum U-Value	$W/(m^2 K)$	1.69	2	2
Space Heating Equipment	Minimum AFUE	91%	90%	GH1 (95%)
Heat Recovery Ventilator (HRV)	Minimum Efficiency	80%	-	V1 (70%)
Domestic Hot Water Heater	Energy Factor	0.67	0.57	GH6 (0.55)
Air Conditioning Minimum	SEER	12	13	AC1 (14)

Note: Environment data taken from (Government of Ontario, 2011) *for OBC,* (CCHT, 2011) *for the As Built, &* (CHBA, 2011) *for the R2000 codes respectively*

Table 4-6: LCCA on LCU Upgrade by Category – Toronto, Ontario

Upgrade	Incremental Cost	Total NPV Cost Case 1	Heating Load	Cooling Load	Exhaust Fan	Furnace Fan	HRV	DHW	App / Lights	Total Eclectic	Total Gas	Total
Item	$ CAD	$ CAD	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	m^3	kWh
Base		$93,343	23087	707	324	570		7735	8760	10361	2908	41183
Case 1		$108,403	18666	692	324	485	762	5276	8760	11023	2259	34964
Case 2a		$142,804	18727	682	324	486	762	1403	8760	11014	1899	31144
Case 2b		$128,219	18727	682	324	474	762	1403	8760	11290	1899	31420
C1	$552	$94,435	22929	712	324	565		7735	8760	10361	2893	41025
C2	$1,397	$96,244	22820	716	324	563		7735	8760	10362	2883	40917
AGW1	$1,321	$96,160	22913	713	324	565		7735	8760	10362	2891	41010
AGW2	$721	$94,270	22345	730	324	551		7735	8760	10365	2838	40445
AGW3	$4,161	$101,344	21625	750	324	533		7735	8760	10367	2770	39727
AGW4	$4,978	$102,809	21221	763	324	523		7735	8760	10370	2732	39325
AGW5	$721	$94,251	22330	730	324	550		7735	8760	10364	2836	40429
AGW6	$4,055	$101,331	21861	744	324	539		7735	8760	10367	2792	39962
AGW7	$4,872	$102,570	21221	763	324	523		7735	8760	10370	2732	39325
AGW8	$20,367	$136,173	19768	809	324	487		7735	8760	10380	2595	37883
BGW2	$1,681	$96,927	22836	721	324	563		7735	8760	10368	2884	40939
BGW3	$3,328	$100,636	22831	721	324	563		7735	8760	10368	2884	40934
BGW4	$4,375	$102,970	22787	725	324	562		7735	8760	10370	2879	40892
BGW5	$4,376	$102,927	22744	725	324	561		7735	8760	10370	2875	40849
BGW6	$12,245	$120,684	22744	725	324	561		7735	8760	10370	2875	40849
EF1	$394	$94,863	22804	735	324	562		7735	8760	10381	2881	40920
EF2	$754	$94,911	22904	721	324	565		7735	8760	10370	2890	41009
BS1	$1,694	$96,979	22802	734	324	562		7735	8760	10380	2881	40917
BS2	$3,295	$100,242	22222	793	324	548		7735	8760	10425	2826	40382
V1	$835	$96,934	20998	655	324	516	762	7735	8760	11017	2711	39749
AC1	$65	$93,441	23050	684	324	568		7735	8760	10336	2904	41121
GH1	$472	$93,594	21837	709	324	568		7735	8760	10361	2790	39933
GH2	$1,030	$93,983	23087	707	324	570		5187	8760	10361	2667	38635
GH3	$1,280	$94,459	23087	707	324	570		4899	8760	10361	2640	38347
GH4	$3,453	$101,309	23087	707	324	570		1485	8760	10361	2318	34933
GH5	$4,646	$101,230	23087	707	324	570		1403	8760	10361	2310	34851
GH6	$968	$93,145	23087	707	324	570		5276	8760	10361	2676	38724

4.6 HOT2000 and TRNSYS Simulation Sensitivity Analysis

The following sections considered a comparison case study of the building simulation model for both HOT2000 and TRNSYS. The reference city in these studies is Toronto, Ontario. The study was broken up into four individual studies and sections as follows:

1) 4.6.1: Comparing Baseline Reference Model
2) 4.6.2: Comparing Case 1 Sensitivity Study
3) 4.6.3: Comparing Case 2a Sensitivity Study
4) 4.6.4: Comparing Case 2b Sensitivity Study

4.6.1 HOT2000 and TRNSYS Simulation Sensitivity Analysis – Baseline Reference Case

The initial portion of the studies involved a comparison of the baseline reference models. Default assumptions were taken from Table 3-3. By comparing the vital building load characteristics (space heating, space cooling, DHW heating, exhaust fan, furnace fan, and appliance consumptions for the baseline reference case), the comparison between the two simulation models was performed. Table 4-7 summarizes the results of this study. Space heating consumptions comparison showed a 6.63% difference, whilst cooling had a 7.46% percent difference. It should be noted that the magnitude of the cooling loads was much smaller; thus, a greater difference. Similar was the case for the exhaust fan load with a deviation of 30.14%. HRV fan loads were not considered in the baseline reference case as these simulation models had no HRV equipment; however, it was created in the subsequent studies. DHW had a differential of 1.91%. Exhaust fan consumption and appliance consumption had no difference. Appliance loads were based on the HOT2000 standard operating conditions. Total consumption loads were 41,183 kWh and 42,969 kWh for TRNSYS and HOT2000, respectively, with a deviation of 4.34%. With the comparison models within five percent of each other, all other models were created with all similar assumption in both softwares for the baseline and Case 1, Case 2a, and Case 2b. As previously mentioned in the report, each of the cases represented the average parameters, 2006 and 2008 gas fuel extreme pricing parameters. All of the economic parameters have been summarized in Table 4-8.

Table 4-7: HOT2000 and TRNSYS Baseline Reference Building Simulation Models – Toronto, ON

Output Parameters	Unit	HOT2000	TRNSYS	% of Difference
		Toronto	Toronto	Toronto
Annual Heating Degree Days (HDD) below 18°C	-	4200	4192	0.19%
Space Heating Consumption	kWh	24,727.22	23,087.00	6.63%
Space Cooling Consumption	kWh	764.00	707.00	7.46%
DHW Heating Consumption	kWh	7,590.00	7,735.00	1.91%
Furnace Fan Consumption	kWh	438.00	570.00	30.14%
Exhaust Fan Consumption	kWh	324.00	324.00	0.00%
HRV Fan Consumption	kWh	0.00	0.00	0.00%
Appliances and lighting consumption[1]	kWh	8,760.00	8,760.00	0.00%
Total Annual Energy Consumptions	**kWh**	**42,969**	**41,183.00**	4.34%

Note
1. The appliances and lighting consumption was based on the standard operating conditions used in the HOT2000 & TRNSYS programs.

4.6.2 HOT2000 and TRNSYS Simulation Sensitivity Analysis – Case 1

As in the previous section of the report, three cases were studied as part of a detailed sensitivity analysis. Case 1 considered the average sensitivity parameters with all case results summarized in Table 4-8, and plotted in Figure 4-9. For Case 1, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $93,343 and $94,630 for TRNSYS and HOT2000, respectively, with a deviation of 1.38%. The difference between initial baseline consumptions was discussed previously, but these differentials were 41,183 kWh and 42,969 kWh with a 4.34 % difference between TRNSYS and HOT2000. The resulting upgrades from round to round were GH6, AC1, GH1, AGW5, C1, EF1, BGW2, BS1, and V1 for TRNSYS, whilst HOT2000 upgrades were GH2, AGW5, AC1, C1, EF1, V1, BS1, and BGW2. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two softwares were essentially the same; the only major difference was the DHW (GH6 and GH2) heating upgrades and the sequence of the upgrades. The resulting total optimal consumption was 34,964 kWh and 34,576 kWh for TRNSYS and HOT2000, respectively, with a deviation of 1.11% between

4.6.3 HOT2000 and TRNSYS Simulation Sensitivity Analysis – Case 2a

Case 2a considered the 2006 natural gas fuel commodity pricing. All case results are summarized in Table 4-8, and plotted in Figure 4-9. For Case 2a, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $152,923 and $158, 258 with a percent deviation of 3.49% between TRNSYS and HOT2000, respectively. The difference between initial baseline consumptions was discussed previously, but these differentials were 41,183 kWh and 42,969 kWh with a 4.34% difference between TRNSYS and HOT2000. The resulting upgrades from round to round were GH5, GH1, V1, AGW5, AC1, C1, EF2, BS1, and BGW2 for TRNSYS, whilst HOT2000 upgrades were GH2, AGW5, V1, C1, AC1, EF1, BS1, and BGW2. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two softwares were essentially the same; the only major difference was the DHW (GH5 and GH2) heating upgrades, flooring upgrades (EF2 and EF1), and the sequence of the upgrades. The resulting total optimal consumption was 31,144 kWh, and 34,576 kWh with a deviation of 11.05% between TRNSYS and HOT2000, respectively.

4.6.4 HOT2000 and TRNSYS Simulation Sensitivity Analysis – Case 2b

Case 2b considered the 2008 natural gas fuel commodity pricing, with all case results summarized in Table 4-8, and plotted in Figure 4-9. For Case 2b, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $128,917 and $132,828 with a percent deviation of 3.03% between TRNSYS and HOT2000, respectively. The difference between initial baseline consumptions was discussed previously, but these differentials were 41,183 kWh and 42,969 kWh with a 4.34% differential between TRNSYS and HOT2000. The resulting upgrades from round to round were GH5, GH1, AGW5, AC1, V1, C1, EF2, BGW2, and BS1 for TRNSYS, whilst HOT2000 upgrades were GH2, AGW5, V1, C1, AC1, EF1, BS1, and BGW2. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW

(GH5 and GH2) heating upgrades, flooring upgrades (EF2 and EF1), and the sequencing of the upgrades. The resulting total optimal consumption was 31,420 kWh, and 34,576 kWh with a deviation of 10.05% between TRNSYS and HOT2000, respectively.

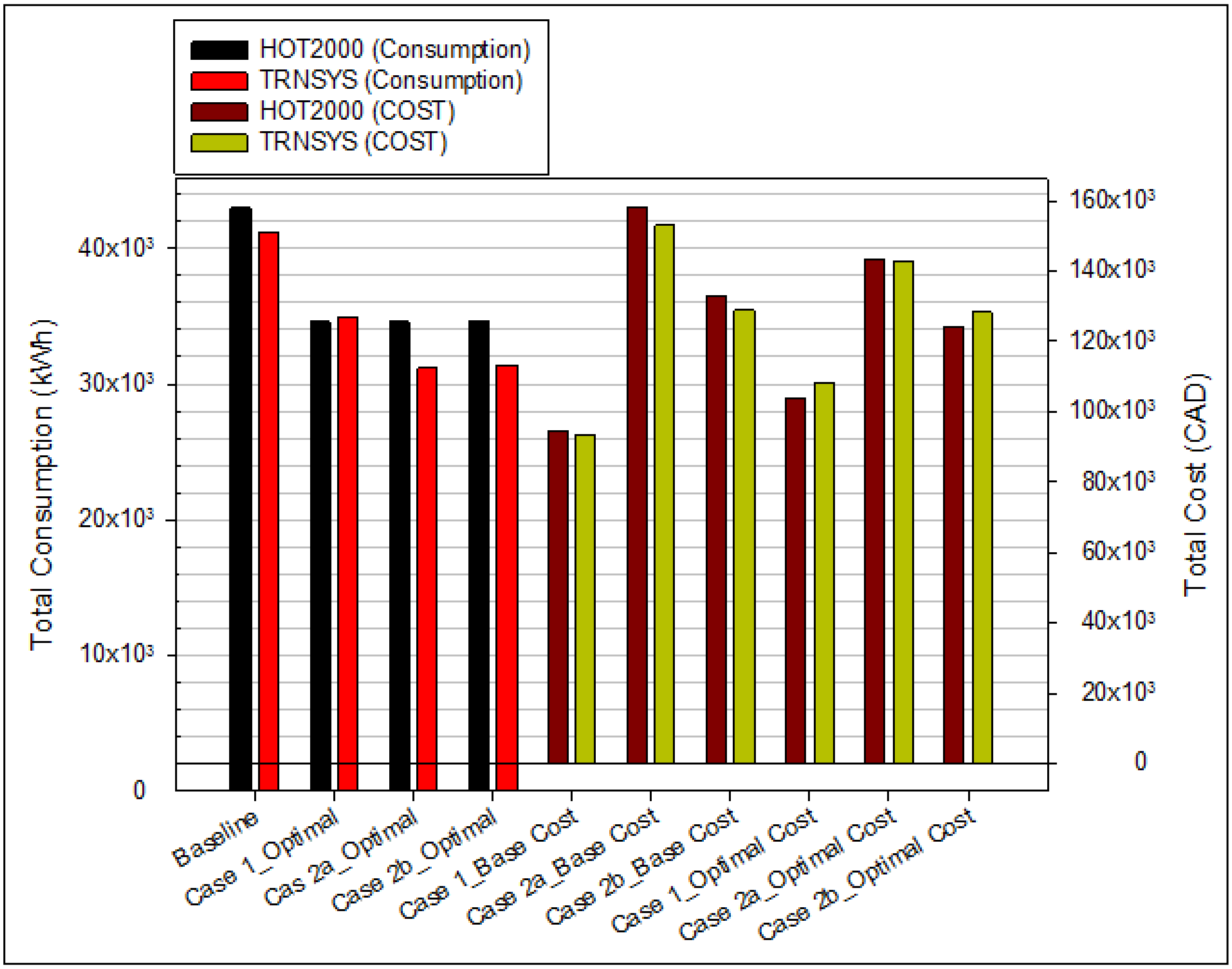


Figure 4-9: Consumption and cost comparison of baseline and optimal upgrades between HOT2000 and TRNSYS

Table 4-8: HOT2000 and TRNSYS Sensitivity Analysis Case 1, Case 2a, and Case 2b –Toronto, Ontario

Toronto, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Parameters							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Inflation	%	1.99		3.10			
Mortgage	%	7.87		5.05			
Electricity Escalation	%	3.50		3.50			
Gas Escalation	%	3.02		5.50			
Tax	%	13.00					
Amortisation	Years	30					
Electricity Pricing Monthly (Includes delivery, debt, supply, transmission, before tax)							
Electricity Price	$ / kWh	0.1038					
> 800 kWh	$ / kWh	0.1138					
Natural Gas Delivery Monthly (Includes delivery, gas supply, storage charge before tax)							
Gas Provider 1	$ / m^3	0.2892		0.7053		0.5300	
Next 55 m3	$ / m^3	0.2843		0.7053		0.5300	
Next 170 m3	$ / m^3	0.2892		0.7053		0.5300	
Over 170 m3	$ / m^3	0.2843		0.7053		0.5300	
Gas Provider 2	$ / m^3	0.2892		0.7152		0.5379	
Next 150 m3	$ / m^3	0.2843		0.7152		0.5379	
Next 250 m3	$ / m^3	0.2892		0.7152		0.5379	
Toronto, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Results							
Parameter	Unit	Case 1		Case 2a		Case 2	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Upgrades By Round							
Upgrades By Round	R1	GH6	GH2	GH5	GH2	GH5	GH2
	R2	AC1	AGW5	GH1	AGW5	GH1	AGW5
	R3	GH1	AC1	V1	V1	AGW5	V1
	R4	AGW5	C1	AGW5	C1	AC1	C1
	R5	C1	EF1	AC1	AC1	V1	AC1
	R6	EF1	V1	C1	EF1	C1	EF1
	R7	BGW2	BS1	EF2	BS1	EF2	BS1
	R8	BS1	BGW2	BS1	BGW2	BGW2	BGW2
	R9	V1	-	BGW2	-	BS1	-
Total Costs & Consumption By Round							
Total Baseline Cost NPV	$	$93,343	$94,630	$152,923	$158,258	$128,917	$132,828
% Difference	%	1.38%		3.49%		3.03%	
Total Optimal Costs NPV	$	$108,403	$103,811	$142,804	$143,216	$128,219	$124,333
% Difference	%	4.24%		0.29%		3.03%	
Total Baseline Consumption	kWh	41,183	42,969	41,183	42,969	41,183	42,969
% Difference	%	4.34%		4.34%		4.34%	
Total Optimal Consumption	kWh	34,964	34,576	31,144	34,576	31,420	34,576
% Difference	%	1.11%		11.05%		10.05%	

Notes:

1. The OME recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.
2. The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).
3. The GHG emission calculation was done using the carbon dioxide (CO^2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO^2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
4. The total life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.
5. 1 cubic meter of natural gas = 37 MJ = 10.6 kWh , 1kWh = 3.6 MJ

Chapter 5

5 Least Cost Analysis for Ontario New Housing

5.1 Overview

In this chapter the combination of the least cost upgrades were determined using the brute force sequential search (BFSS) method for climate conditions in Ottawa, Thunder Bay, and Windsor, Ontario. In chapter 4, the same methodology was used to determine the least cost upgrades for Toronto, Ontario. The reference city in this study is Toronto, Ontario. The weather condition in Ottawa and Thunder Bay is much colder than Toronto. The estimated heating degree days (HDD) (below 18°) for both cities are (Dembo, 2011):

1) Ottawa: 4602
2) Thunder Bay: 5677

Windsor has a warmer climate than Toronto with heating degree days (HDD) of 3525 (Dembo, 2011). The results are discussed below.

5.2 HOT2000 and TRNSYS Simulation Sensitivity Analysis

5.2.1 HOT2000 and TRNSYS Sensitivity Analysis – Ottawa, Ontario

The following sections considered a comparison case study of the building simulation model for both HOT2000 and TRNSYS. The study was broken up into four individual studies and sections as follows:

1) 5.2.2: Comparing Baseline Reference Model
2) 5.2.3: Comparing Case 1 Sensitivity Study
3) 5.2.4: Comparing Case 2a Sensitivity Study
4) 5.2.5: Comparing Case 2b Sensitivity Study

5.2.2 HOT2000 and TRNSYS Sensitivity Analysis Baseline Case – Ottawa, Ontario

The initial portion of the studies involved a comparison of the baseline reference models. Defaults assumptions were taken from Table 3-3. By comparing the vital building load characteristics (space heating, space cooling, DHW heating, exhaust fan, furnace fan, and appliance consumptions for the baseline reference case), the comparison between the two simulation models was performed. Table 5-1 summarizes the results of this study. Space heating consumptions comparison showed a 10.84% difference, whilst cooling had a 12.91% difference. It should be noted that the magnitude of the cooling loads was much smaller; thus, a greater difference. Similar was the case for the furnace fan load with a deviation of 24.36%. HRV fan loads were not considered in the baseline reference case as these simulation models had no HRV equipment, however were created in the subsequent studies. DHW had a difference of 0.24%. Exhaust fan consumption and appliance consumption had no difference. Appliance loads were based on the HOT2000 standard operating conditions. Total consumption loads were 44,202 kWh and 47,701 kWh for TRNSYS and HOT2000, resulting with a deviation of 7.92%. With the comparison models within 7.92% of each other, all other models created in both softwares were performed on Case 1, Case 2a, and Case 2b. As previously mentioned in the report, each of the cases represented the average parameters, 2006, and 2008 natural gas fuel pricing parameters. All of the economic parameters have been summarized in Table 5-2.

Table 5-1: HOT2000 and TRNSYS Baseline Reference Building Simulation Models – Toronto, ON

Output Parameters	**Unit**	**HOT2000**	**TRNSYS**	**% of Difference**
		Ottawa	**Ottawa**	**Toronto**
Annual Heating Degree Days (HDD) below 18°C	-	4600	4720	2.5%
Space Heating Consumption	kWh	29,206	26,041	10.84%
Space Cooling Consumption	kWh	796	693	12.91%
DHW Heating Consumption	kWh	7,762	7,744	0.24%
Exhaust Fan Consumption	kWh	324	324	0.00%
Furnace Fan Consumption	kWh	517	643	24.36%
HRV Fan Consumption	kWh	N/A	N/A	N/A
Appliances and Lighting Consumption[1]	kWh	8,760.00	8,760	0.00%
Total Annual Energy Consumptions	**kWh**	**47,701**	**44,202**	7.92%

Note

1. The appliances and lighting consumption was based on the standard operating conditions used in the HOT2000 and TRNSYS program.

5.2.3 HOT2000 and TRNSYS Sensitivity Analysis Case 1 – Ottawa, Ontario

As in the previous section of the report, three cases were studied as part of a detailed sensitivity analysis. Case 1 considered the average sensitivity parameters with all case results summarized in Table 5-2. For Case 1, the BFSS method was simulated in both TRNSYS and HOT2000, the results were then compared. Baseline reference model costs were $96,473 and $99,357 for TRNSYS and HOT2000, respectively, with a deviation of 2.99%. The differential between initial baseline consumptions were discussed previously, but were 44,202 kWh and 47,701 kWh with a 7.92% differential between TRNSYS and HOT2000. The resulting upgrades from round to round were AC1, AGW1, BGW2, GH6, GH1, EF2, C1, V1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH2, AGW1, BGW2, EF1, AC1, C1, V1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two softwares were essentially the same; the only major difference was the DHW (GH6 and GH2) heating upgrades and the sequence of the upgrades. The resulting total optimal consumption was 37,284 kWh and 39,304 kWh for TRNSYS and HOT2000, respectively, with a deviation of 5.42%.

5.2.4 HOT2000 and TRNSYS Sensitivity Analysis Case 2a – Ottawa, Ontario

Case 2a considered the 2006 natural gas fuel commodity pricing, all case results summarized in Table 5-2. For Case 2a, the BFSS method was simulated in both TRNSYS and HOT2000, the results were then compared. Baseline reference model costs were $162,217 and $173,144 for TRNSYS and HOT2000, respectively, with a deviation of 6.74%. The differences between initial baseline consumptions were discussed previously, but these differences were 44,202 kWh and 47,701 kWh for TRNSYS and HOT2000, respectively, with a deviation of 7.92%. The resulting upgrades from round to round were GH4, GH1, V1, BGW2, AGW1, AC1, EF2, C1, and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, AGW7, V1, BGW2, C1, EF1, AC1 and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH4 and GH3) heating upgrades, flooring upgrades

(EF2 and EF1), above grade wall (AGW1 and AGW7), and the sequence of the upgrades. The resulting total optimal consumption was 34,265 kWh and 36,353 kWh for TRNSYS and HOT2000, respectively, with a deviation of 6.09%.

5.2.5 HOT2000 and TRNSYS Sensitivity Analysis Case 2b – Ottawa, Ontario

Case 2b considered the 2008 natural gas fuel commodity pricing, all case results summarized in Table 5-2. For Case 2b, the BFSS method was simulated in both TRNSYS and HOT2000, the results were then compared. Baseline reference model costs were $136,137 and $144,067 for TRNSYS and HOT2000, respectively, with a deviation of 5.82%. The differences between initial baseline consumptions were discussed previously, but these differences were 44,202 kWh and 47,701 kWh for TRNSYS and HOT2000, respectively, with a deviation of 7.92%. The resulting upgrades from round to round were GH6, GH1, V1, AGW1, BGW2, AC1, EF2, C1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, AGW7, V1, BGW2, EF1, C1, AC1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH6 and GH3) heating upgrades, flooring upgrades (EF2 and EF1), above grade wall (AGW1 and AGW7), and the sequence of the upgrades. The resulting total optimal consumption was 38,066 kWh and 36,353 kWh for TRNSYS and HOT2000, respectively, with a deviation of 4.50%.

Table 5-2: HOT2000 and TRNSYS Sensitivity Analysis – Ottawa, ON

Ottawa, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Parameters							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Inflation	%	1.99		3.10			
Mortgage	%	7.87		5.05			
Electricity Escalation	%	3.50		3.50			
Gas Escalation	%	3.02		5.50			
Tax	%	13.00					
Amortisation	Years	30					
Electricity Pricing Monthly (Includes delivery, debt, supply, transmission, before tax)							
Electricity Price	$\$ / kWh$	0.1038					
> 800 kWh	$\$ / kWh$	0.1138					
Natural Gas Delivery Monthly (Includes delivery, gas supply, storage charge before tax)							
Gas Provider 1	$\$ / m^3$	0.2892		0.7053		0.5300	
Next 55 m3	$\$ / m^3$	0.2843		0.7053		0.5300	
Next 170 m3	$\$ / m^3$	0.2892		0.7053		0.5300	
Over 170 m3	$\$ / m^3$	0.2843		0.7053		0.5300	
Gas Provider 2	$\$ / m^3$	0.2892		0.7152		0.5379	
Next 150 m3	$\$ / m^3$	0.2843		0.7152		0.5379	
Next 250 m3	$\$ / m^3$	0.2892		0.7152		0.5379	

Ottawa, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Results							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Upgrades By Round							
Upgrades By Round	R1	AC1	GH2	GH4	GH3	GH6	GH3
	R2	AGW1	AGW1	GH1	AGW7	GH1	AGW7
	R3	BGW2	BGW2	V1	V1	V1	V1
	R4	GH6	EF1	BGW2	BGW2	AGW1	BGW2
	R5	GH1	AC1	AGW1	C1	BGW2	EF1
	R6	EF2	C1	AC1	EF1	AC1	C1
	R7	C1	V1	EF2	AC1	EF2	AC1
	R8	V1	BS1	C1	BS1	C1	BS1
	R9	BS1	-	BS1	-	BS1	-
Total Costs & Consumption By Round							
Total Baseline Cost NPV	$\$$	$96,473	$99,357	$162,217	$173,144	$136,137	$144,067
% Difference	%	2.99%		6.74%		5.82%	
Total Optimal Costs NPV	$\$$	$105,324	$105,887	$153,436	$154,150	$133,794	$133,827
% Difference	%	0.53%		0.47%		0.02%	
Total Baseline Consumption	kWh	44,202	47,701	44,202	47,701	44,202	47,701
% Difference	%	7.92%		7.92%		7.92%	
Total Optimal Consumption	kWh	37,284	39,304	34,265	36,353	38,066	36,353
% Difference	%	5.42%		6.09%		4.50%	

Notes:

1. The OME recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.
2. The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).
3. The GHG emission calculation was done using the carbon dioxide (CO^2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO^2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
4. The total life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.
5. 1 cubic meter of natural gas = 37 MJ = 10.6 kWh , 1kWh = 3.6 MJ

5.2.6 HOT2000 and TRNSYS Sensitivity Analysis – Thunder Bay, Ontario

The following sections considered a comparison case study of the building simulation model for both HOT2000 and TRNSYS. The study was broken up into four individual studies and sections as follows:

1) 5.2.7: Comparing Baseline Reference Model
2) 5.2.8: Comparing Case 1 Sensitivity Study
3) 5.2.9: Comparing Case 2a Sensitivity Study
4) 5.2.10: Comparing Case 2b Sensitivity Study

5.2.7 HOT2000 and TRNSYS Sensitivity Analysis Baseline Case – Thunder Bay, Ontario

The initial portion of the studies involved a comparison of the baseline reference models. Defaults assumptions were taken from Table 3-3. By comparing the vital building load characteristics (space heating, space cooling, DHW heating, exhaust fan, furnace fan, and appliance consumptions for the baseline reference case), comparison between the two simulation models was performed. Table 5-3 summarizes the results of this study. A comparison of space heating consumptions showed a 1.53% difference, whilst cooling had a 26.36% difference. It should be noted that the magnitude of the cooling loads was much smaller thus resulting in, a greater percentage difference. Similar case was for the furnace fan load with a deviation of 36.66%. HRV fan loads were not considered in the baseline reference case as these simulation models had no HRV equipment; however, it was created in the subsequent studies. DHW had a difference of 7.85%. Exhaust fan consumption and appliance consumption had no difference. Appliance loads were based on the HOT2000 standard operating conditions. Total consumption loads were 49,328 kWh and 50,754 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.81%. With the comparison models within 2.81% of each other, all other models created in both softwares were performed on Case 1, Case 2a, and Case 2b. As previously mentioned in the report, each of the cases represented the average parameters, 2006, and 2008 natural gas fuel extreme pricing parameters. All of the economic parameters have been summarized in Table 5-4.

Table 5-3: HOT2000 and TRNSYS Baseline Reference Building Models – Thunder Bay, Ontario

Output Parameters	Unit	HOT2000	TRNSYS	% of Difference
		Thunder Bay	Thunder Bay	Thunder Bay
Space Heating Consumption	kWh	32,157	31,667	1.53%
Space Cooling Consumption	kWh	515	379	26.36%
DHW Heating Consumption	kWh	8,052	7,420	7.85%
Exhaust Fan Consumption	kWh	324	324	0.00%
Furnace Fan Consumption	kWh	569	778	36.66%
HRV Fan Consumption	kWh	N/A	N/A	N/A
Appliances and Lighting Consumption[1]	KWh	8,760	8,760	0.00%
Total Annual Energy Consumptions	**kWh**	**50,754**	**49,328**	2.81%

Note

1. The appliances and lighting consumption was based on the standard operating conditions used in the HOT2000 & TRNSYS programs.

5.2.8 HOT2000 and TRNSYS Sensitivity Analysis Case 1 – Thunder Bay, Ontario

As in the previous section of the report, three cases were studied as part of a detailed sensitivity analysis. Case 1 considered the average sensitivity parameters with all case results summarized in Table 5-4. For Case 1, the BFSS method was simulated in both TRNSYS and HOT2000, the results were then compared. Baseline reference model costs were \$100,438 and \$101,486 for TRNSYS and HOT2000, respectively, with a deviation of 1.04%. The differences between initial baseline consumptions were discussed previously, but these differences were 49,328 kWh and 50,754 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.89%. The resulting upgrades from round to round were AGW7, AC1, BGW2, GH6, EF2, C1, GH1, V1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH2, BGW2, EF1, AC1, AGW7, C1, V1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo–boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH6 and GH2) heating upgrades, flooring upgrades (EF2 and EF1), and the sequencing of the upgrades. The resulting total optimal consumption was 40,752 kWh and 41,637 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.17%.

5.2.9 HOT2000 and TRNSYS Sensitivity Analysis Case 2a – Thunder Bay, Ontario

Case 2a considered the 2006 natural gas fuel commodity pricing, all case results summarized in Table 5-4. For Case 2a, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $178,376 and $182,547 for TRNSYS and HOT2000, respectively, with a deviation of 2.34%. The difference initial baseline consumptions were discussed previously, but they were 49,328 kWh and 50,754 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.89%. The resulting upgrades from round to round were GH5, AGW7, V1, GH1, BGW2, AC1, EF2, C1, and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, V1, AGW7, BGW2, C1, EF1, AC1 and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH5 and GH3) heating upgrades, flooring upgrades (EF2 and EF1), and the sequence of the upgrades. The resulting total optimal consumption was 37,255 kWh and 41,405 kWh for TRNSYS and HOT2000, respectively, with a deviation of 11.14%.

5.2.10 HOT2000 and TRNSYS Sensitivity Analysis Case 2b – Thunder Bay, Ontario

Case 2b considered the 2008 natural gas fuel commodity pricing, all case results summarized in Table 5-4. For Case 2b, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $147,933 and $150,926 TRNSYS and HOT2000, respectively, with a deviation of 2.02%. The differences between initial baseline consumptions were discussed previously, but they were 49,328 kWh and 50,754 kWh with a 2.89% difference between TRNSYS and HOT2000. The resulting upgrades from round to round were AGW7, GH6, V1, GH1, BGW2, AC1, EF2, C1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, V1, BGW2, AGW7, C1, EF1, AC1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo – boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH6 and GH3) heating upgrades, flooring upgrades (EF2 and EF1), and the sequence of the upgrades. The resulting total optimal consumption was 40,752 kWh and 41,405 kWh for TRNSYS and HOT2000, respectively, with a deviation of 1.60%.

Table 5-4: HOT2000 and TRNSYS Sensitivity Analysis – Thunder Bay - Ontario

Thunder Bay, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Parameters							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Inflation	%	1.99		3.10			
Mortgage	%	7.87		5.05			
Electricity Escalation	%	3.50		3.50			
Gas Escalation	%	3.02		5.50			
Tax	%	13.00					
Amortisation	Years	30					
Electricity Pricing Monthly (Includes delivery, debt, supply, transmission, before tax)							
Electricity Price	$ / kWh	0.1038					
> 800 kWh	$ / kWh	0.1138					
Natural Gas Delivery Monthly (Includes delivery, gas supply, storage charge before tax)							
Gas Provider 1	$ / m^3	0.2892		0.7053		0.5300	
Next 55 m3	$ / m^3	0.2843		0.7053		0.5300	
Next 170 m3	$ / m^3	0.2892		0.7053		0.5300	
Over 170 m3	$ / m^3	0.2843		0.7053		0.5300	
Gas Provider 2	$ / m^3	0.2892		0.7152		0.5379	
Next 150 m3	$ / m^3	0.2843		0.7152		0.5379	
Next 250 m3	$ / m^3	0.2892		0.7152		0.5379	
Thunder Bay, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Results							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Upgrades By Round							
Upgrades By Round	R1	AGW7	GH2	GH5	GH3	AGW7	GH3
	R2	AC1	BGW2	AGW7	V1	GH6	V1
	R3	BGW2	EF1	V1	AGW7	V1	BGW2
	R4	GH6	AC1	GH1	BGW2	GH1	AGW7
	R5	EF2	AGW7	BGW2	C1	BGW2	C1
	R6	C1	C1	AC1	EF1	AC1	EF1
	R7	GH1	V1	EF2	AC1	EF2	AC1
	R8	V1	BS1	C1	BS1	C1	BS1
	R9	BS1	-	BS1	-	BS1	-
Total Costs & Consumption By Round							
Total Baseline Cost NPV	$	$100,438	$101,486	$178,376	$182,547	$147,933	$150926
% Difference	%	1.04%		2.34%		2.02%	
Total Optimal Costs NPV	$	$111,160	$107,117	$162,629	$163,414	$140,140	$138,968
% Difference	%	3.64%		0.48%		0.84%	
Total Baseline Consumption	kWh	49,328	50,754	49,328	50,754	49,328	50,754
% Difference	%	2.89%		2.89%		2.89%	
Total Optimal Consumption	kWh	40,752	41,637	37,255	41,405	40,752	41,405
% Difference	%	2.17%		11.14%		1.60%	

Notes:

1. The OME recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.
2. The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).
3. The GHG emission calculation was done using the carbon dioxide (CO^2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO^2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
4. The total life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.
5. 1 cubic meter of natural gas = 37 MJ = 10.6 kWh , 1kWh = 3.6 MJ

5.2.11 HOT2000 and TRNSYS Sensitivity Analysis – Windsor, Ontario

The following sections considered a comparison case study of the building simulation model for both HOT2000 and TRNSYS. The study was broken up into four individual studies and sections as follows:

1) 5.2.12: Comparing Baseline Reference Model
2) 5.2.13: Comparing Case 1 Sensitivity Study
3) 5.2.14: Comparing Case 2a Sensitivity Study
4) 5.2.15: Comparing Case 2b Sensitivity Study

5.2.12 HOT2000 and TRNSYS Sensitivity Analysis Baseline Case – Windsor, Ontario

The initial portion of the studies involved a comparison of the baseline reference models. Default assumptions were taken from Table 3-3. By comparing the vital building load characteristics (space heating, space cooling, DHW heating, exhaust fan, furnace fan, and appliance consumptions for the baseline reference case), comparison between the two simulation models was performed. Table 5-5 summarizes the results of this study. A comparison of space heating consumptions showed a 3.49% difference, whilst cooling had a 20.55% difference. It should be noted that the magnitude of the cooling loads were much smaller, thus, resulting in a greater difference. A similar was the furnace fan load with a deviation of 34.38%. HRV fan loads were not considered in the baseline reference case as these simulation models had no HRV equipment; however, these were created in the subsequent studies. DHW had a difference of 3.85%. Exhaust fan consumption and appliance consumption had no difference. Appliance loads were based on the HOT2000 standard operating conditions. Total consumption loads were 38,985 kWh and 39,814 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.08%. With the comparison models within 2.08% of each other, all other models created in both softwares were performed on Case 1, Case 2a, and Case 2b. As previously mentioned in the report, each of the cases represented the average parameters, 2006, and 2008 natural gas fuel extreme pricing parameters. All of the economic parameters have been summarized in Table 5-6.

Table 5-5: HOT2000 and TRNSYS Baseline Reference Building Models – Windsor, Ontario

Output Parameters	Unit	HOT2000	TRNSYS	% of Difference
		Windsor	Windsor	Windsor
Space Heating Consumption	kWh	21,396	20,649	3.49%
Space Cooling Consumption	kWh	1,135	902	20.55%
DHW Heating Consumption	kWh	7,551	7,842	3.85%
Exhaust Fan Consumption	kWh	324	324	0.00%
Furnace Fan Consumption	kWh	379	509	34.38%
HRV Fan Consumption	kWh	N/A	N/A	N/A
Appliances and Lighting Consumption[1]	kWh	8,760	8,760	0.00%
Total Annual Energy Consumptions	**kWh**	**39,814**	**38,985**	2.08%

Note

1. The appliances and lighting consumption was based on the standard operating conditions used in the HOT2000 & TRNSYS programs.

5.2.13 HOT2000 and TRNSYS Sensitivity Analysis Case 1 – Windsor, Ontario

As in the previous section of the report, three cases were studied as part of a detailed sensitivity analysis. Case 1 considered the average sensitivity parameters with all case results summarized in Table 5-6. For Case 1, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $91,435 and $92,466 for TRNSYS and HOT2000, respectively, with a deviation of 1.13%. The differences between initial baseline consumptions were discussed previously, but they were 38,985 kWh and 39,814 kWh with a 2.13% difference between TRNSYS and HOT2000. The resulting upgrades from round to round were GH6, AC1, AGW1, BGW2, GH1, EF2, C1, V1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH2, AGW1, BGW2, AC1, EF1, C1, V1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH2 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo–boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH6 and GH2) heating upgrades, flooring upgrades (EF2 and EF1), and the sequence of the upgrades. The resulting total optimal consumption was 32,751 kWh and 32,770 kWh for TRNSYS and HOT2000, respectively, with a deviation of 0.06%.

5.2.14 HOT2000 and TRNSYS Sensitivity Analysis Case 2a – Windsor, Ontario

Case 2a considered the 2006 natural gas fuel commodity pricing, all case results summarized in Table 5-6. For Case 2a, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $145,905 and $148,555 for TRNSYS and HOT2000, respectively, with a deviation of 1.82%. The differences between initial baseline consumptions were discussed previously, but they were 38,985 kWh and 39,814 kWh with a 2.13% difference between TRNSYS and HOT2000. The resulting upgrades from round to round were GH5, GH1, V1, BGW2, AGW1, AC1, EF2, C1, and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, AGW7, V1, BGW2, EF1, C1, AC1 and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo–boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH5 and GH3) heating upgrades, flooring upgrades (EF2 and EF1), above grade wall (AGW1 and AGW7), and the sequence of the upgrades. The resulting total optimal consumption was 29,742 kWh and 30,406 kWh for TRNSYS and HOT2000, respectively, with a deviation of 2.23%.

5.2.15 HOT2000 and TRNSYS Sensitivity Analysis Case 2b – Windsor, Ontario

Case 2b considered the 2008 natural gas fuel commodity pricing, all case results summarized in Table 5-6. For Case 2b, the BFSS method was simulated in both TRNSYS and HOT2000; the results were then compared. Baseline reference model costs were $123,948 and $125,766 for TRNSYS and HOT2000, respectively, with a deviation of 1.47%. The differences between initial baseline consumptions were discussed previously, but they were 38,985 kWh and 39,814 kWh with a 2.13% difference between TRNSYS and HOT2000. The resulting upgrades from round to round were GH6, GH1, BGW2, AGW1, AC1, EF2, C1 and BS1 for TRNSYS, whilst HOT2000 upgrades were GH3, AGW1, V1, BGW2, EF1, AC1, C1, and BS1. It should be noted that HOT2000 only had eight upgrades, whilst TRNSYS had nine, due to the GH3 upgrade for HOT2000, incorporating both DHW and furnace upgrades, as the equipment was a combo–boiler system. The upgrades between the two software were essentially the same; the only major difference was the DHW (GH6 and GH3) heating upgrades, flooring upgrades (EF2 and EF1), and the sequencing of the upgrades. The resulting total optimal consumption was 33,632 kWh and 32,544 kWh for TRNSYS and HOT2000, respectively, with a deviation of 3.24%.

Table 5-6: HOT2000 and TRNSYS Sensitivity Analysis – Windsor, Ontario

Windsor, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Parameters							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Inflation	%	1.99		3.10			
Mortgage	%	7.87		5.05			
Electricity Escalation	%	3.50		3.50			
Gas Escalation	%	3.02		5.50			
Tax	%	13.00					
Amortisation	Years	30					
Electricity Pricing Monthly (Includes delivery, debt, supply, transmission, before tax)							
Electricity Price	$ / kWh	0.1038					
> 800 kWh	$ / kWh	0.1138					
Natural Gas Delivery Monthly (Includes delivery, gas supply, storage charge before tax)							
Gas Provider 1	$ / m^3	0.2892		0.7053		0.5300	
Next 55 m3	$ / m^3	0.2843		0.7053		0.5300	
Next 170 m3	$ / m^3	0.2892		0.7053		0.5300	
Over 170 m3	$ / m^3	0.2843		0.7053		0.5300	
Gas Provider 2	$ / m^3	0.2892		0.7152		0.5379	
Next 150 m3	$ / m^3	0.2843		0.7152		0.5379	
Next 250 m3	$ / m^3	0.2892		0.7152		0.5379	
Windsor, Ontario - TRNSYS & HOT2000: Sensitivity Analysis Results							
Parameter	Unit	Case 1		Case 2a		Case 2b	
		TRNSYS	HOT2000	TRNSYS	HOT2000	TRNSYS	HOT2000
Upgrades By Round							
Upgrades By Round	R1	GH6	GH2	GH5	GH3	GH6	GH3
	R2	AC1	AGW1	GH1	AGW7	GH1	AGW1
	R3	AGW1	BGW2	V1	V1	BGW2	V1
	R4	BGW2	AC1	BGW2	BGW2	AGW1	BGW2
	R5	GH1	EF1	AGW1	EF1	AC1	EF1
	R6	EF2	C1	AC1	C1	EF2	AC1
	R7	C1	V1	EF2	AC1	C1	A1
	R8	V1	BS1	C1	BS1	V1	BS1
	R9	BS1	-	BS1	-	BS1	-
Total Costs & Consumption By Round							
Total Baseline Cost NPV	$	$91,435	$92,466	$145,905	$148,555	$123,948	$125,766
% Difference	%	1.13%		1.82%		1.47%	
Total Optimal Costs NPV	$	$102,757	$99,724	$137,848	$134,709	$122,729	$118,523
% Difference	%	2.95%		2.28%		3.43%	
Total Baseline Consumption	kWh	38,985	39,814	38,985	39,814	38,985	39,814
% Difference	%	2.13%		2.13%		2.13%	
Total Optimal Consumption	kWh	32,751	32,770	29,742	30,406	33,632	32,544
% Difference	%	0.06%		2.23%		3.24%	

Notes:

1. The OME recently announced that the projected long-term electricity price increase of 3.50% annually for the next twenty years (OME, 2010). Therefore, 3.50% will be used as the identified electricity escalation rate for the proposed methodology.
2. The commodity prices for natural gas in 2006 and 2008, respectively, were determined based on the historical data provided by the OEB (2008).
3. The GHG emission calculation was done using the carbon dioxide (CO^2) factors determined from the study by Fung & Gill (2011). In their study, 1.856 kg/m^3 equivalent CO^2 (NRCan, 2006) was used for natural gas, and the average emission factor for electricity was 226.35 tons CO2/total gigawatt-hour (GWh) generation (Gordon & Fung, 2009).
4. The total life cycle cost (LCC) was determined based on the identified average mortgage rate of 7.87%, average discount rate of 1.99%, and the fuel escalation rates for electricity and natural gas of 3.50%, and 3.02%, respectively.
5. 1 cubic meter of natural gas = 37 MJ = 10.6 kWh , 1kWh = 3.6 MJ

Chapter 6

6 Conclusion and Recommendations

6.1 Conclusion

The objective of this report was to present the methodology for determining least cost upgrades in new residential housing using the brute force sequential search (BFSS) method, and to integrate these energy efficient upgrades into a reference CCHT house that will reduce energy consumption while minimizing the NPV of life cycle costs.

The results showed that, based on the life cycle cost analysis of 30 years, all of the identified combinations of least cost upgrades including building envelope, domestic hot water, heating, cooling, furnace, and ventilation systems, the resulting were:

1) Up to 32% reduction in annual energy consumption and 29% in greenhouse gas for Toronto, Ontario
2) Up to 29% reduction in annual energy consumption and 26% in greenhouse gas for Ottawa, Ontario
3) Up to 32% reduction in annual energy consumption and 29% in greenhouse gas for Thunder Bay, Ontario
4) Up to 31% reduction in annual energy consumption and 27% in greenhouse gas for Windsor, Ontario

Economic conditions effects the sequence of the upgrades. When the gas pricing becomes high, the more energy efficient upgrades for DHW get selected at a cost premium. By considering case 1 (average economic condition), with an 18% saving in energy consumption, $15,060 extra spending is needed in initial NPV costs. However, as gas prices increase, the energy efficiency goes up to 32% (case 2a, the extreme condition), whilst reducing initial NPV costs by $10,119. Table 6-1 describes this in detail. Some of the results to highlight are as follows:

The most cost effective upgrades that can be performed on residential housing in Toronto to minimize energy consumption are:

Case 1: Domestic Hot Water (GH6, GH1), Cooling Systems (AC1), Above Grade Wall (AGW5), Ceiling Insulation (C1), Floor insulation (EF1), Below Grade Wall insulation (BGW2), Basement Slab insulation (BS1), and Heat Recovery Ventilator (V1)

Case 2a: Domestic Hot Water (GH5, GH1), Heat Recovery Ventilator (V1), Above Grade Wall insulation (AGW5), Cooling Systems (AC1), Ceiling Insulation (C1), Floor insulation (EF2), Basement Slab insulation (BS1), and Below Grade Wall insulation (BGW2)

Case 2b: Domestic Hot Water (GH5, GH1), Above Grade Wall insulation (AGW5), Cooling Systems (AC1), Heat Recovery Ventilator (V1), Ceiling Insulation (C1), Floor insulation (EF2), Below Grade Wall insulation (BGW2), and Basement Slab insulation (BS1)

The upgrades are in order of minimized cost and energy consumption over the life span of a mortgage. The selection and sequence of these upgrades have a direct correlation with economic conditions. With a high gas commodity price, the more energy efficiency upgrades that get selected for DHW are at a cost premium. It can be shown that Case1 (average economic condition) which saves 18% in energy consumption, requires spending $15,060 extra in initial cost. Cases 2a and 2b (extreme economic condition) save 32% and 31% in energy consumption, increasing the initial cost by $10,119 and $698. However, as gas commodity prices raise, the energy efficiency goes up, while reducing the initial cost. Table 6-1 shows the comparison result of reduction in the estimated annual energy consumption for Toronto, Ottawa, Thunder Bay, and Windsor.

Table 6-1: TRNSYS & HOT2000 reduction in the estimated annual energy consumption, Ontario

	Case 1			Case 2a			Case 2b		
Toronto									
	TRNSYS	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**
Total Baseline Cost NPV	$93,343	$94,630		$152,923	$158,258		$128,917	$132,828	
Total Optimal Costs NPV	$108,403	$103,811		$142,804	$143,216		$128,219	$124,333	
$ Difference	$15,060	$9,181		-$10,119	-$15,042		-$ 698	-$8,495	
Total Baseline Consumption	41,183	42,969	7.74	41,183	42,969	7.74	41,183	42,969	7.74
Total Optimal Consumption	34,964	34,576	6.69	31,144	34,576	6.02	31,420	34,576	6.08
% Difference	18%	24%	16%	32%	24%	29%	31%	24%	27%
Ottawa									
	Case 1			**Case 2a**			**Case 2b**		
	TRNSYS	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**
Total Baseline Cost NPV	$96,473	$99,357		$162,217	$173,144		$136,137	$144,067	
Total Optimal Costs NPV	$105,324	$105,887		$153,436	$154,150		$133,794	$133,827	
$ Difference	$8,851	$6,530		-$8,781	-$18,994		-$2,343	-$10,240	
Total Baseline Consumption	44,202	47,701	8.27	44,202	47,701	8.27	44,202	47,701	8.27
Total Optimal Consumption	37,284	39,304	7.06	34,265	36,353	6.57	38,066	36,353	7.23
% Difference	19%	21%	17%	29%	31%	26%	16%	31%	14%
Thunder Bay									
	Case 1			**Case 2a**			**Case 2b**		
	TRNSYS	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**
Total Baseline Cost NPV	$100,438	$101,486		$178,376	$182,547		$147,933	$150,926	
Total Optimal Costs NPV	$111,160	$107,117		$162,629	$163,414		$140,140	$138,968	
$ Difference	$10,722	$5,631		-$15,747	-$19,133		-$7,793	-$11,958	
Total Baseline Consumption	49,328	50,754	9.16	49,328	50,754	9.16	49,328	50,754	9.16
Total Optimal Consumption	40,752	41,637	7.69	37,255	41,405	7.08	40,752	41,405	7.69
% Difference	21%	22%	19%	32%	23%	29%	21%	23%	19%
Windsor									
	Case 1			**Case 2a**			**Case 2b**		
	TRNSYS	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**	**TRNSYS**	**HOT2000**	**GHG (T)**
Total Baseline Cost NPV	$91,435	$92,466		$145,905	$148,555		$123,948	$125,766	
Total Optimal Costs NPV	$102,757	$99,724		$137,848	$134,709		$122,729	$118,523	
$ Difference	$11,322	$7,258		-$8,057	-$13,846		-$1,219	-$7,243	
Total Baseline Consumption	38,985	39,814	7.36	38,985	39,814	7.36	38,985	39,814	7.36
Total Optimal Consumption	32,751	32,770	6.31	29,742	30,406	5.78	33,632	32,544	6.46
% Difference	19%	21%	17%	31%	31%	27%	16%	22%	14%

6.2 Recommendations

To further develop the area of this work, this methodology can be used in a variety of situations. The recommendations have been mentioned in the main sections that were developed for the purpose of this work as:

1. Selection of upgrades: A number of technologies are available in the market for the residential sectors. Using this report as a basis, the potential feasibility of other technologies and upgrades can be studied to further minimize energy consumption in residential housing, not only in Toronto, but in other Canadian cities.

2. Building codes studies: There currently exist multitudes of building codes across Canada (NRC, 2005). These codes are all completely or partially based upon the current building codes across Canada using a variety of municipal and provincial experts that modify the codes as technology changes every five years or so. But how effective are these codes in relation not only to the NBCC but also to each other, and what sort of carbon footprints are they leaving? Studies should be done to see the potentials of regional building codes versus the national building code and how they stack up to one another. Localized studies can also be performed on a city-by-city basis with the proposed methodology in order to see how green residential structures in cities across Canada, and also in other areas of the world.

3. Life Cycle Cost Analysis: It was the purpose of this report to account for the energy consumption costs, fuel costs, materials costs, and other such costs as explained in previous chapters. However, for any true life cycle costing scenarios completing LCCA needs to be performed, to determine the predicted energy consumption from raw material extraction to disposable or recycling as shown in numerous studies (Haines, et al., 2007; Dong, et al., 2005; Wolfgang, 1997). The use of other softwares and tools such as Athena (Athena Institute, 2011) can further enhance these results.

4. Energy Modeling: It was the intent of this paper to use TRNSYS (Solar Energy Laboratory, 2011) for the building modeling simulation portion of this study. However, there are numerous software packages available on the market (US Department of Energy, 2005), that

could have been used for the building simulation models. Further validation of the results can be done by using other commercially available packages and validating the building simulation data between packages. One of the shortcomings in the use of the TRNSYS simulation software was its lack of a computer aided design. This CAD interface and building information modeling interfaces would have aided to visualize the model and aid in robust building envelope modifications and transferring legacy data between building simulation softwares such as Energy Plus (US Department of Energy, 2011) and REVIT (Autodesk, 2011), since there was such a multitude of prescriptive upgrades.

5. Benchmarking: In any energy system, realistic validation cannot occur unless physical testing is performed. Some of the proposed upgrades or upgrades currently built-to-code should be compared to real time data to see the percent deviations of the results.

Appendix A

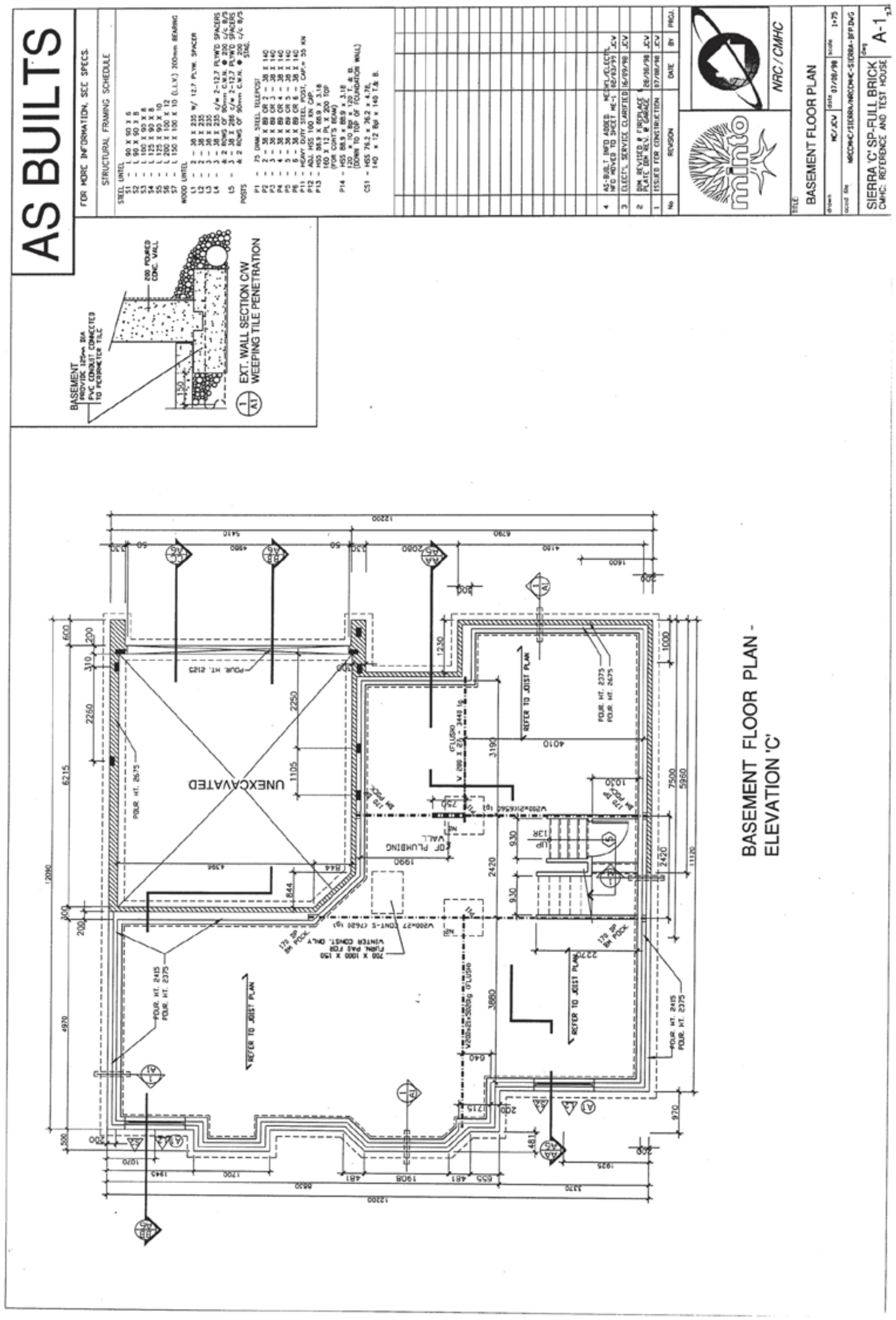
A: Tables

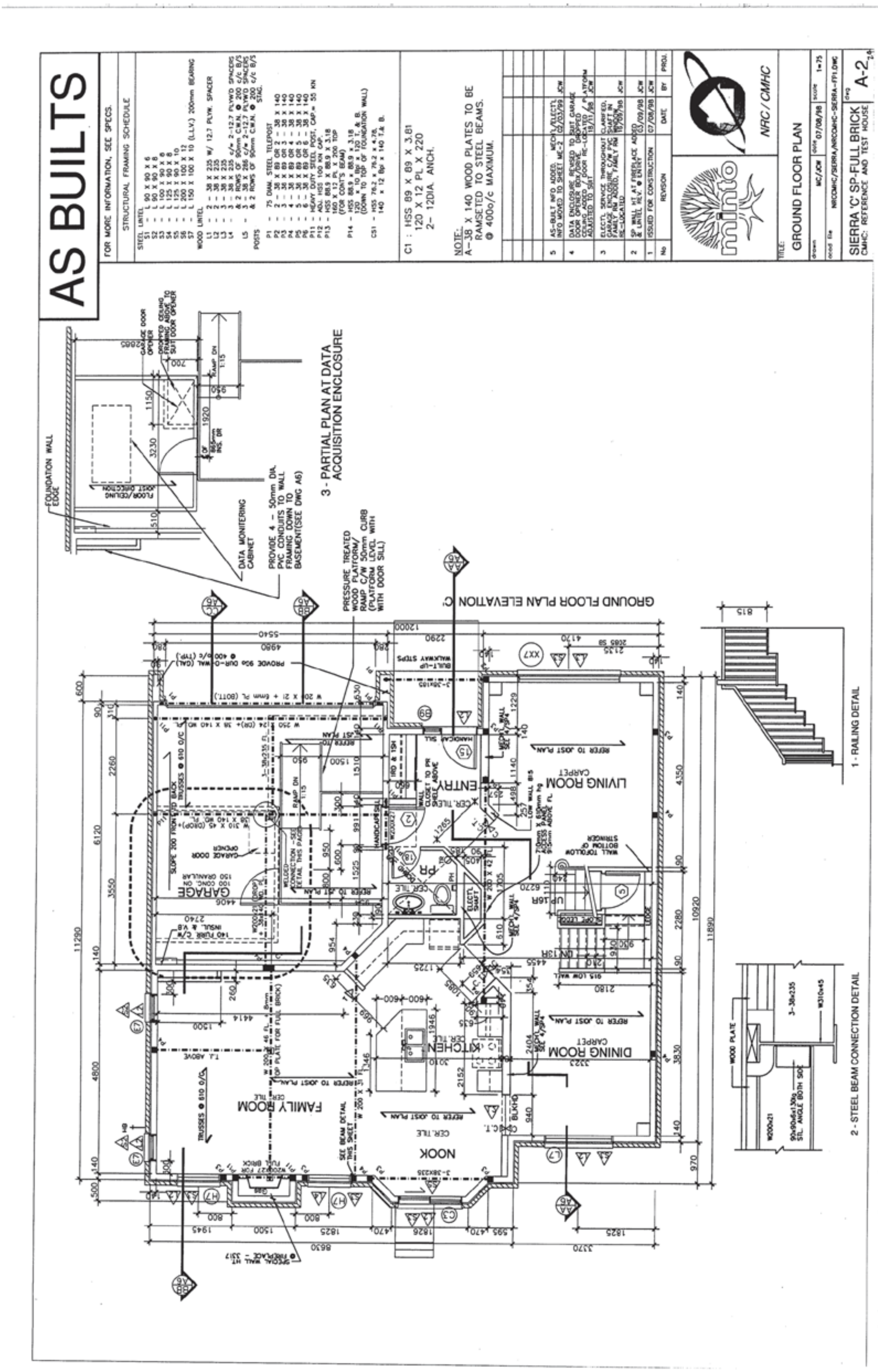
Table A-1: LCU Analysis of Upgrades by Cost, Consumption – Toronto, Ontario

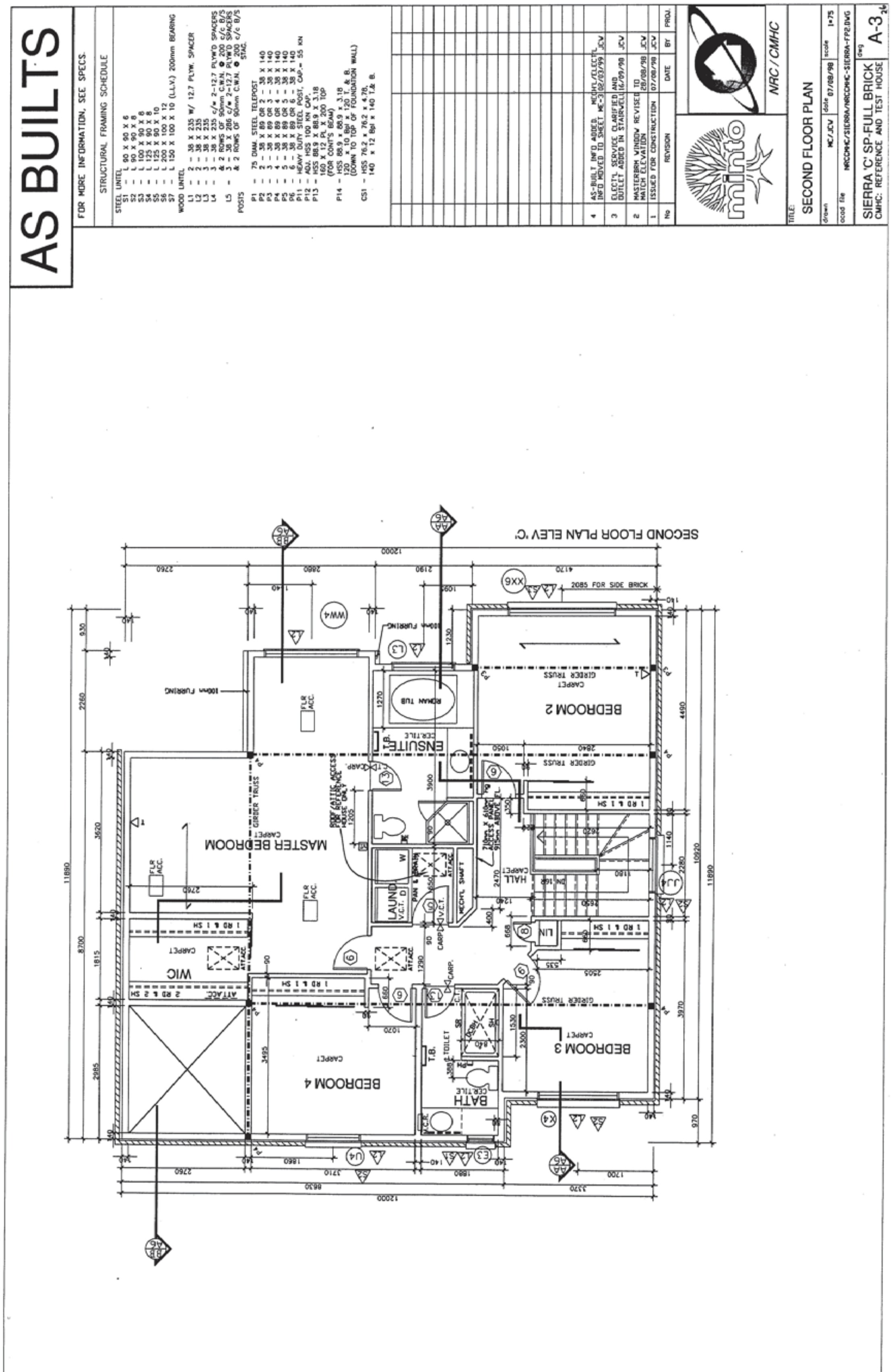
Round 1	Upgrade	Incremental Cost	Total NPV Cost Case 1	Total NPV Cost Case 2a	Total NPV Cost Case 2b	Heating Load	Cooling Load	Exhaust Fan	Furnace Fan	HRV	DHW	App / Lights	Total Electric	Total Gas	Total
Item	Item	$ CAD	$ CAD	$ CAD	$ CAD	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	m^3	kWh
Base	**Base**		$93,343	$152,923	$128,917	23087	707	324	570		7735	8760	10361	2908	41183
C-1	**Case 1**		$108,403			18666	692	324	485	762	5276	8760	11023	2259	34964
C-2a	**Case 2a**			$142,804		18727	682	324	486	762	1403	8760	11014	1899	31144
C-2b	**Case 2b**				$128,219	18727	682	324	474	762	1403	8760	11290	1899	31420
1	**C1**	$552	$94,435	$153,222	$129,339	22929	712	324	565		7735	8760	10361	2893	41025
2	**C2**	$1,397	$96,244	$154,104	$130,306	22820	716	324	563		7735	8760	10362	2883	40917
3	**AGW1**	$1,321	$96,160	$154,284	$130,413	22913	713	324	565		7735	8760	10362	2891	41010
4	**AGW2**	$721	$94,270	$151,650	$128,221	22345	730	324	551		7735	8760	10365	2838	40445
5	**AGW3**	$4,161	$101,344	$154,356	$131,488	21625	750	324	533		7735	8760	10367	2770	39727
6	**AGW4**	$4,978	$102,809	$154,276	$131,723	21221	763	324	523		7735	8760	10370	2732	39325
7	**AGW5**	$721	$94,251	$151,600	$128,183	22330	730	324	550		7735	8760	10364	2836	40429
8	**AGW6**	$4,055	$101,331	$154,941	$131,890	21861	744	324	539		7735	8760	10367	2792	39962
9	**AGW7**	$4,872	$102,570	$154,123	$131,571	21221	763	324	523		7735	8760	10370	2732	39325
10	**AGW8**	$20,367	$136,173	$171,932	$150,511	19768	809	324	487		7735	8760	10380	2595	37883
11	**BGW2**	$1,681	$96,927	$154,586	$130,775	22836	721	324	563		7735	8760	10368	2884	40939
12	**BGW3**	$3,328	$100,636	$156,941	$133,135	22831	721	324	563		7735	8760	10368	2884	40934
13	**BGW4**	$4,375	$102,970	$158,323	$134,551	22787	725	324	562		7735	8760	10370	2879	40892
14	**BGW5**	$4,376	$102,927	$158,187	$134,448	22744	725	324	561		7735	8760	10370	2875	40849
15	**BGW6**	$12,245	$120,684	$169,526	$145,787	22744	725	324	561		7735	8760	10370	2875	40849
16	**EF1**	$394	$94,863	$153,581	$129,795	22804	735	324	562		7735	8760	10381	2881	40920
17	**EF2**	$754	$94,911	$153,472	$129,608	22904	721	324	565		7735	8760	10370	2890	41009
18	**BS1**	$1,694	$96,979	$154,545	$130,761	22802	734	324	562		7735	8760	10380	2881	40917
19	**BS2**	$3,295	$100,242	$155,210	$131,878	22222	793	324	548		7735	8760	10425	2826	40382
20	**V1**	$835	$96,934	$151,229	$128,850	20998	655	324	516	762	7735	8760	11017	2711	39749
21	**AC1**	$65	$93,441	$152,939	$128,961	23050	684	324	568		7735	8760	10336	2904	41121
22	**GH1**	$472	$93,594	$150,019	$126,987	21837	709	324	568		7735	8760	10361	2790	39933
23	**GH2**	$1,030	$93,983	$147,046	$125,025	23087	707	324	570		5187	8760	10361	2667	38635
24	**GH3**	$1,280	$94,459	$146,656	$124,859	23087	707	324	570		4899	8760	10361	2640	38347
25	**GH4**	$3,453	$101,309	$145,901	$126,763	23087	707	324	570		1485	8760	10361	2318	34933
26	**GH5**	$4,646	$101,230	$142,604	$123,530	23087	707	324	570		1403	8760	10361	2310	34851
27	**GH6**	$968	$93,145	$146,604	$124,513	23087	707	324	570		5276	8760	10361	2676	38724

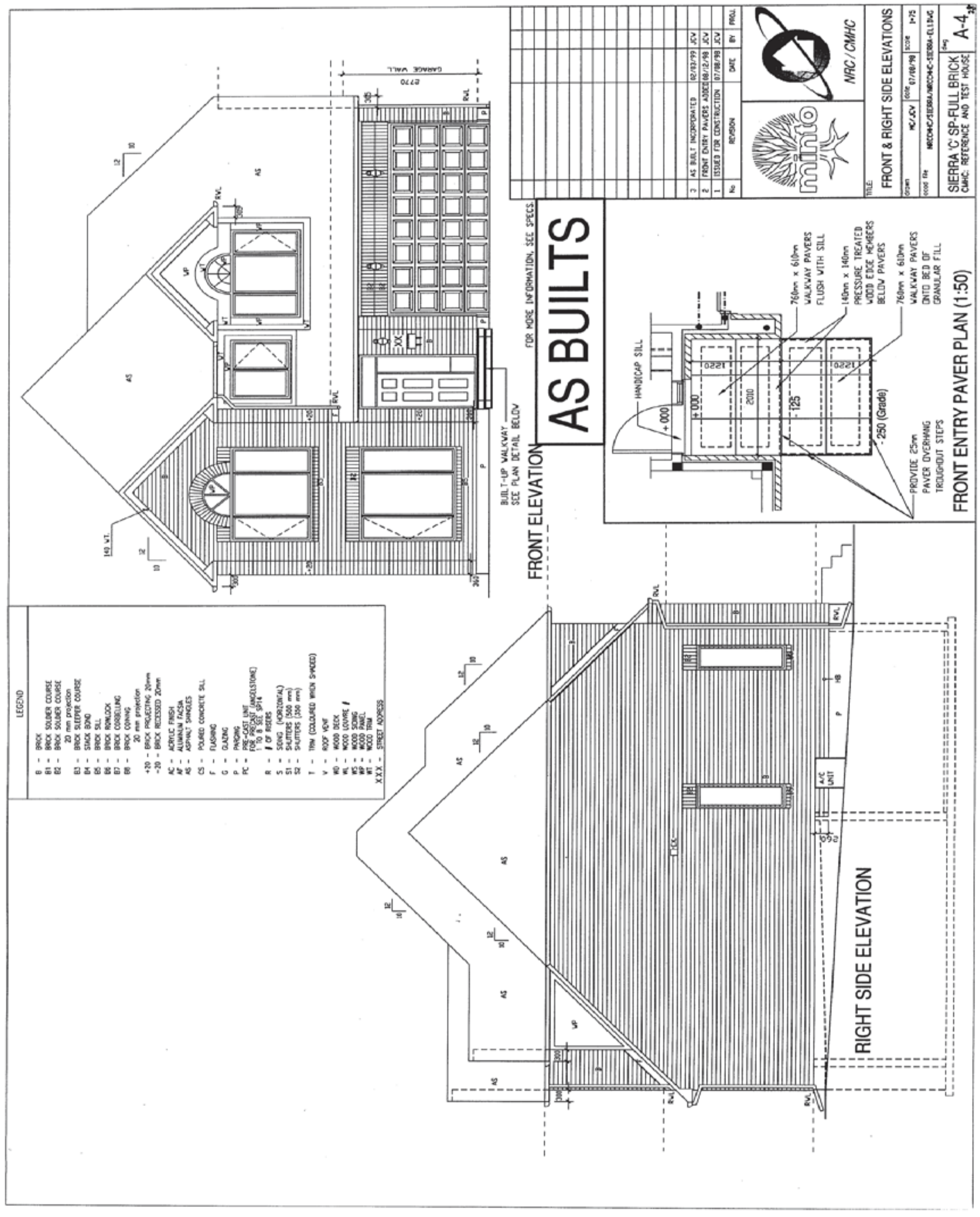
Appendix B

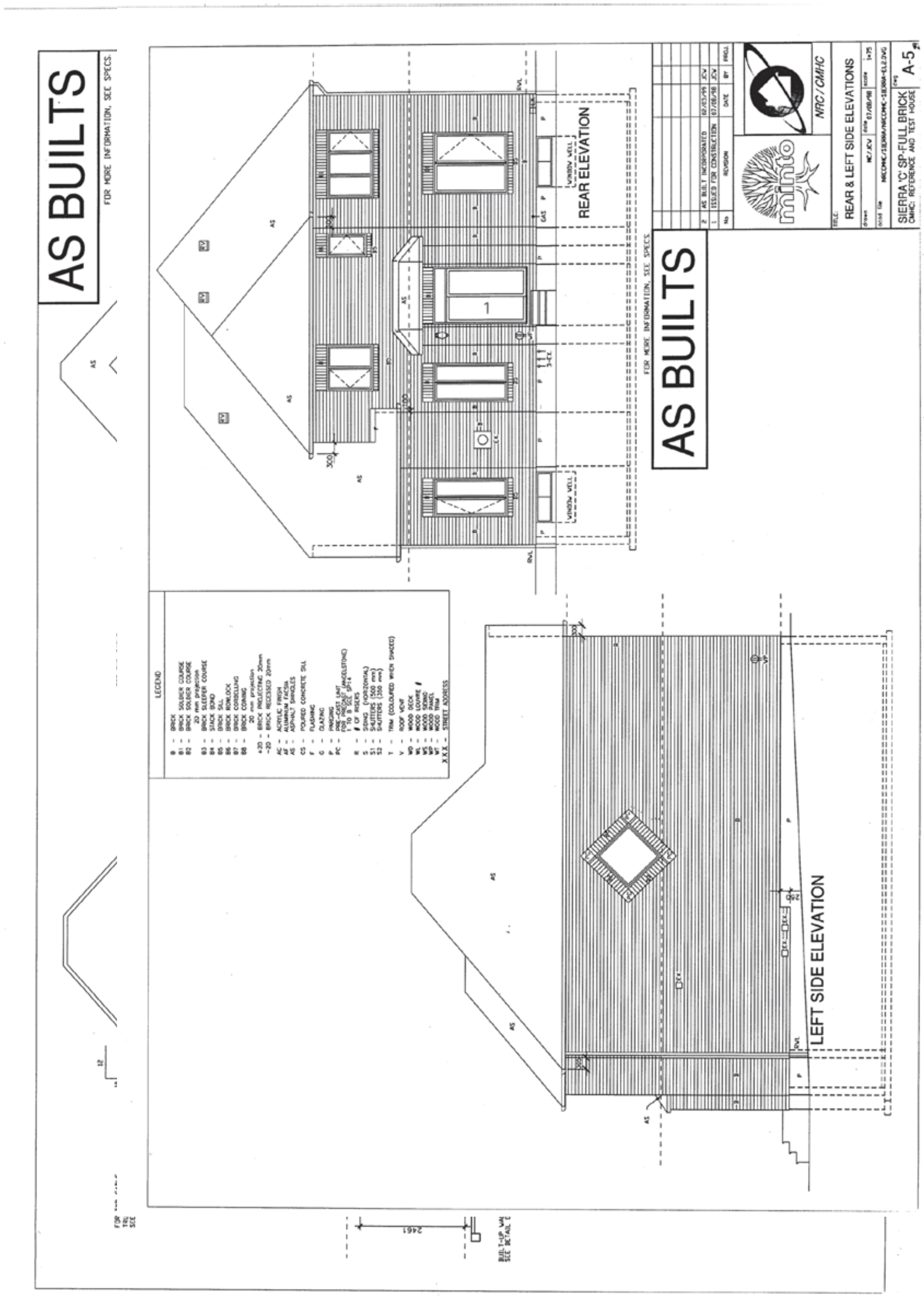
B: Architectural Drawings of the CCHT Reference House


AS BUILTS
EXT. WALL SECTION C/W WEEPING TILE PENETRATION
UNEXCAVATED
BASEMENT FLOOR PLAN - ELEVATION 'C'
NRC / CMHC
BASEMENT FLOOR PLAN
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
A-1


AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
STRUCTURAL FRAMING SCHEDULE
C1 : HSS 89 X 89 X 3.81
120 X 12 PL X 220
2- 12DIA. ANCH.
NOTE:
A-38 X 140 WOOD PLATES TO BE
RAMSETED TO STEEL BEAMS.
@ 400o/c MAXIMUM.
NRC / CMHC
GROUND FLOOR PLAN
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
A-2
3 - PARTIAL PLAN AT DATA
ACQUISITION ENCLOSURE
GROUND FLOOR PLAN ELEVATION 'C'
FAMILY ROOM
GARAGE
NOOK
KITCHEN
DINING ROOM
LIVING ROOM
ENTRY
2 - STEEL BEAM CONNECTION DETAIL
1 - RAILING DETAIL


AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
STRUCTURAL FRAMING SCHEDULE
SECOND FLOOR PLAN ELEV 'C'
MASTER BEDROOM
BEDROOM 2
BEDROOM 3
BEDROOM 4
ENSUITE
BATH
HALL
LAUND
WIC
ROMAN TUB
NRC / CMHC
SECOND FLOOR PLAN
SIERRA 'C' SP-FULL BRICK
CMHC: REFERENCE AND TEST HOUSE
A-3


AS BUILTS
FRONT ELEVATION
RIGHT SIDE ELEVATION
FRONT ENTRY PAVER PLAN (1:50)
LEGEND
NRC/CMHC
FRONT & RIGHT SIDE ELEVATIONS
SIERRA 'C' SP-FULL BRICK
A-4


AS BUILTS
FOR MORE INFORMATION, SEE SPECS.
REAR ELEVATION
LEFT SIDE ELEVATION
LEGEND
REAR & LEFT SIDE ELEVATIONS
SIERRA 'C' SP-FULL BRICK
CMHC REFERENCE AND TEST HOUSE
NRC/CMHC
A-5

Appendix C

C: Nomenclature

ACH	Air-Change per Hour
AC	Air-Conditioning
ASHP	Air-Source Heat Pump
AFUE	Annual Fuel Utilization efficiency
BTU/Btu	British Thermal Units
BA	Building America
CMHC	Canada Mortgage and Housing Corporation
CCHT	Canadian Centre for Housing Technology
CDN	Canadian Dollars
CGBC	Canadian Green Building Council
CHBA	Canadian Home Builders' Association
CREEM	Canadian Residential Energy End-use Model
U or U-value	Coefficient of heat transfer [W/m2K or Btu/f2hrF]
CFM	Cubit-Feet per Minute
DOE	Department of Energy
DHW	Domestic hot-water
DWHR/GWHR	Drain/Grey Water Heat Recovery
ECO	Energy Conservation Opportunities
ECM	Electronically Commutated Motor
EGNH	EnerGuide for New Houses
EF	Energy Factor
EIA	Energy Information Administration
ER	Energy Rating
ESNH	ENERGY STAR for New Homes
EPA	Environmental Protection Agency
GA	Genetic Algorithms
GJ	Gigajoule
GTA	Greater Toronto Area
GHG	Green House Gas
GHCC	Greenhouse Certified Construction
GCHP	Ground-Coupled Heat Pump
GSHP	Ground-Source Heat Pump
HRV	Heat Recovery Ventilator

HVAC	Heating, Ventilating, and Air Conditioning
ICFs	Insulated Concrete Forms
J	Joule
kWh	Kilo-Watt Hour
LEED	Leadership in Energy and Environmental Design
LEEDH	LEED for Homes
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCEA	Life Cycle Energy Assessment
LCU	Least Cost Upgrades
Low-E	Low Emissivity
MJ	Mega joule
Mt	Megatons
MBH	Million BTU(Btu) per Hour
MMAH	Ministry of Municipal Affairs and Housing
MNECB	Model National Energy Code for Buildings
NAHB	National Association of Home Builders
NBCC	National Building Code of Canada
NRCC	National Research Council of Canada
NRCan	Natural Resources Canada
NPV	Net Present Value
NZE or ZNE	Net Zero (or Zero Net) Energy
ON	Ontario
OBC	Ontario Building Code
Pa	Pascal
PJ	Petajoules
PV	Photovoltaic
PEI	Prince Edward Island
SIR	Saving-to-Investment Ratio
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SIPs	Structural Insulated Panels
SHEU	Survey of Household Energy Use
RSI or R-value	Thermal resistance [m2K/W or f2hrF/Btu]
TRNSYS	Transient Systems Simulation
US	United States

Appendix D

D: Glossary

C	**Ceiling**
C2	RSI 10.57 (R60) Insulation
AGW	**Above Grade Wall**
AGW2	RSI 4.22 (R24) Insulation
AGW3	RSI 4.75 (R27) Insulation
AGW4	RSI 5.10 (R29) Insulation
AGW5	RSI 4.22 (R24) Insulation @ 600 mm (24 in.) o/c
AGW6	RSI 4.57 (R26) Insulation @ 600 mm (24 in.) o/c
AGW7	RSI 5.10 (R29) Insulation @ 600 mm (24 in.) o/c
AGW8	RSI 7.00 (R40) Insulation
BGW	**Below Grade Walls**
BGW1	RSI 2.11 (R12) Insulation, Exterior
BGW2	RSI 3.5 (R20) Insulation
BGW3	RSI 3.5 (R20) Insulation, Exterior
BGW4	RSI 3.87 (R22) Insulation
BGW5	RSI 4.22 (R24) Insulation
BGW6	RSI 4.22 (R24) Insulation (ICFs)
EF	**Exposed Floor**
EF1	RSI 5.45 (R31) Insulation
EF2	RSI 5.10 (R29) Insulation
BS	**Basement Slab**
BS1	RSI 2.11 (R12) Insulation
BS2	RSI 3.5 (R20) Insulation
V	**Ventilation**
V1	HRV @ 70% Efficiency
AC	**Cooling**
AC1	SEER of 14
GH	**Gas Heating**
GH1	Furnace w/ ECM @ 90% AFUE
GH2	DHW Heater @ 85% AFUE
GH3	DHW Heater @ 90% AFUE
GH4	Solar-Assisted DHW @ 85% AFUE
GH5	Solar-Assisted DHW @ 90% AFUE
GH6	Drain Water Heat Recovery @ 55% Efficiency

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