Life cycle optimization of envelope and mechanical systems for a single-family house in Quebec

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ABSTRACT

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The environmental impact of residential buildings has been demonstrated to be significant, and to be a result of both their construction and operation. This study therefore looks at the best strategies to minimize life cycle energy consumption (LCE), as well as cost (LCC), for a single-family house in Quebec.

First, an optimization model for the envelope is built, and includes a detailed TRNSYS simulation which computes the operation energy use, embodied energy of material and cost data. It is coupled to GenOpt, a general optimization program, to find the minimum LCC and LCE values, using a Particle Swarm Optimization algorithm. The optimal envelopes and a code compliant envelope are then modeled with various combinations of space conditioning and domestic hot water systems, to evaluate the impact of energy efficient mechanical systems on cost and energy.

It is shown that energy efficient mechanical systems are a better investment than envelope efficiency measures, from a LCC perspective. The optimal combination found is a minimal code compliant envelope with a ground-source heat pump and a desuperheater. These research results suggest that future building code improvements should also cover in detail the performance of mechanical systems, instead of focusing mostly on envelope characteristics.

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Nomenclature

Symbol	Description	Units
ε_c	Thermal conversion efficiency of solar collector	-
η	Intercept efficiency of solar collector	-
A	Area of the horizontal opening between the first and second floors	m^2
A_0	Value of recurring cost at year 1	$
a	Conversion factor to obtain an hourly mass flow rate for convection between floors 1 and 2	$s \cdot kg/hr \cdot m^3$
a_1	Solar collector efficiency equation slope	$W/m^2 \cdot K$
a_2	Solar collector efficiency equation curvature	$W/m^2 \cdot K^2$
b_1	First order incident angle modifier for solar collector efficiency	-
b_2	Second order incident angle modifier for solar collector efficiency	-
c_1	Cognitive acceleration constant for the Particle Swarm Optimization (PSO)	-
c_2	Social acceleration constant for the PSO	-
C_{energy}	Cost of operation energy	$
$C_{investment}$	Cost of envelope at year 0	$
$C_{M\&R}$	Cost of maintenance and replacement of envelope components	$
$COP_{cooling}$	Coefficient of performance for the cooling system	-
COP_{GSHP}	Coefficient of performance of the ground-source heat pump	-
cp_{air}	Specific heat of air	$J/kg \cdot °C$
cp_{water}	Specific heat of water	$J/kg \cdot °C$
d	Real discount rate	-

D	Nominal discount rate	-
day	Day indicator (0 or 1)	-
DSH_{cap}	Heating capacity of the ground-source heat pump with desuperheater	W
e	Real escalation rate for electricity cost	-
$Energy_{Op}$	Operation energy for heating and cooling over the house lifespan	MJ
F	Value of objective function for envelope optimization	-
$F_{primary}$	Conversion coefficient from site-used energy to primary energy	-
F_t	Amount of money spent at the year of occurrence	$
$Flow_{HP1}$	Mass flow rate of liquid leaving the first stage of the ground-source heat pump	kg/hr
$Flow_{HP2}$	Mass flow rate of liquid leaving the second stage of the ground-source heat pump	kg/hr
$FlowT_{borehole}$	Temperature of the incoming liquid into the ground-source heat pump borehole	°C
$FlowT_{HP1}$	Temperature of liquid leaving the first stage of the ground-source heat pump	°C
$FlowT_{HP2}$	Temperature of liquid leaving the second stage of the ground-source heat pump	°C
G	Incident solar radiation	W/m²
g	Gravitational acceleration	m/s²
H	Thickness of partition between the first and second floors	m
H_N	Sherman's infiltration model correction factor for building height	-

LCC_{env}	Total life cycle cost for yhe house envelope	$
LCC_{max}	Maximum value of LCC found for the envelope	$
LCC_{min}	Minimum value of LCC found for the envelope	$
LCE_{2x6R}	Life cycle embodied energy for the 2”x6” wood stud structure of roof	MJ
$LCE_{IncR2x8}$	Incremental life cycle embodied energy for the 2”x8” wood stud structure of roof	MJ
$LCE_{assembly}$	Life cycle embodied energy for an assembly of the house envelope	MJ
LCE_{env}	Total life cycle energy for a house envelope	MJ
LCE_{max}	Maximum value of LCE found for the envelope	MJ
LCE_{min}	Minimum value of LCE found for the envelope	MJ
LCE_{Roof}	Life cycle embodied energy for the roof	MJ
$load_{heating}$	Heating load for one heating season	MJ
$load_{cooling}$	Cooling load for one cooling season	MJ
L_N	Sherman’s infiltration model correction factor for leakiness	-
$m1$	Ventilation mass flow rate for first floor	kg/hr
$m2$	Ventilation mass flow rate for second floor	kg/hr
$mbasement$	Ventilation mass flow rate for basement	kg/hr
m_{conv}	Balanced air flow rate between the first and second floors	kg/hr
$\dot{m}_d$	Mass flow rate of water through the desuperheater	kg/s
$\dot{m}_{reheat}$	Mass flow rate of air passing the reheating element	kg/s
n	Period of time over which a cost is recurring	years
N	Correlation factor for Sherman’s infiltration model	-
N_0	Leakage-infiltration ratio	-

Nday	Number of the day of the year	-
p	Best particle position for the PSO	-
P_{reheat}	Power of the reheating element for ventilation air	W
$PV_{recurring}$	Present value of an annually recurring cost	$
PV_{single}	Present value of a cost occurring a single time	$
$q_{compDHW}$	Extra electrical power needed by the compressor to heat the water through the desuperheater	W
r	Random number used the in the PSO	-
RSI	Thermal resistance	m²·K/W
RTCellu	Thickness of blown cellulose insulation for the roof	m
RTFiber	Thickness of fibreglass insulation for the roof	m
RTPolyi	Thickness of polyisocyanurate insulation for the roof	m
RTPolyu	Thickness of polyurethane insulation for the roof	m
S	Inverse of the cosine of the incidence angle of the sun on the solar collector	-
$Season_{coolon}$	Cooling season indicator (0 or 1)	-
$Season_{heaton}$	Heating season indicator (0 or 1)	-
S_N	Sherman's infiltration model correction factor for shielding	-
Stage	Stage of the ground-source heat pump (negative when in cooling)	-
T1	Average air temperature of the first floor	K
T2	Average air temperature of the second floor	K
T_{air_in}	Temperature of fresh air leaving the heat recovery ventilator	°C
$T_{d,in}$	Temperature of water entering the desuperheater	°C
$T_{d,out}$	Temperature of water leaving the desuperheater	°C

Tmains	Temperature of city water mains	°C
Tsetpoint	Heating setpoint temperature for all three zones of the house	°C
$Tsetpoint_{cool}$	Cooling setpoint temperature for all three zones of the house	°C
v	Velocity vector used in the PSO	-
w1	Weighting factor for envelope LCC	-
w2	Weighting factor for envelope LCE	-
x	Vector defining the position of the particle in the PSO	-

Abbreviations

ACH	Air change per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient of performance
DB	Dry bulb temperature
DHW	Domestic hot water
EER	Energy efficiency ratio (for cooling devices)
GSHP	Ground-source heat pump
HDD	Hour degree day
HRV	Heat recovery ventilator
HSPF	Heating seasonal performance factor
IAM	Incidence angle modifier
IEA	International Energy Agency
LCA	Life cycle analysis
LCC	Life cycle cost
LCE	Life cycle energy
LCGHGE	Life cycle greenhouse gas emissions
LCI	Life cycle inventory
PEX	Cross-linked polyethylene
SEER	Seasonal energy efficiency ratio (for cooling devices)
WB	Wet bulb temperature
XPS	Extruded polystyrene

1. Introduction

Many studies before this one have emphasized the importance of building impacts on resource depletion, energy consumption and climate change. We are now well aware that residential buildings use up to 17% of all energy in Canada (Natural Resources Canada, 2010), and that construction of buildings in general deplete a large portion of wood, mineral and water reserves (Dixit et al., 2010). Despite increased awareness of the environmental impact of buildings, we cannot say that a majority of new houses have been built to significantly higher energy efficiency standards than those who were already attained in the 1990's.

In Quebec, a voluntary program for single-family houses, named Novo-Climat, was put in place in the early 2000's, in order to reduce their energy consumption by about 25% over standard building regulations, which had remained unchanged since 1992. However, in 2010, only 15% of new houses were built to meet Novo-Climat requirements (Protégez-vous, 2010). In 2012, most of these requirements were incorporated to the new building regulations (Ressources Naturelles Québec, 2012), but it can be agreed that we need more progressive and aggressive regulations in order to achieve environmental goals such as Quebec government's target of a 20% green house gases reduction with respect to 1990 levels by 2020. (Gouvernement du Québec, 2012). Many European countries are taking much more radical action to lead the way towards very low energy buildings. For instance, France has a new legislation that requires all new buildings to minimally have a net-zero energy consumption by 2020 (MEDDE, 2012).

In Quebec, there does not seem to be a consensus on the direction to take to tackle the issue of growing energy consumption. For many decades, numerous environmentalists have advocated that energy efficiency measures in buildings are more cost effective than the plan put forward by the government until now, which mainly consisted in building new hydroelectric plants.

However, it seems like more demonstration of the potential of energy efficiency for home owners is required in order to convince the population to make the right decisions, and the government, to apply more stringent codes to new houses.

1.1. Research objectives

This thesis aims at making recommendations on the best path to pursue energy efficiency in single-family houses, in a way that is economically and environmentally viable, so it can be demonstrated to be attractive to home buyers. With this in mind, two sub-objectives are undertaken:

1. To optimize a single-family house envelope from a life cycle cost and life cycle energy perspective, using parameters that reflect the real cost and service life of a new prototype house in Quebec, as proposed by the Happy Modular company.

2. To evaluate the life cycle cost and energy of various well established mechanical systems for space conditioning and domestic hot water for different house envelopes.

2. Literature review

In this chapter, the state of life cycle assessment (LCA) and optimization of green buildings is studied. First, this literature review aims at listing a selection of successful low-energy and eco-friendly housing projects in Canada, in order to reflect the reality of the national market. These serve as examples of envelopes and of mechanical systems that are applicable to cold climates. Then, the relevance and methodology implication of performing LCA on building is reviewed. Thirdly, life cycle analyses and optimizations of buildings from various locations in cold climates around the world are presented, in order to draw conclusions on the economical and environmental impacts of green buildings design alternatives. The methodology previously used and presented in the scientific literature is also of interest.

2.1. Green housing in Canada

2.1.1. CMHC's Equilibrium Housing Demonstration Projects

In the past few years, many green housing projects were created in Canada. Some of them were part of governmental research programs, such as the EQuilibrium Housing Demonstration Projects (CMHC, 2011). The objective of this program was to demonstrate the feasibility of net-zero energy houses in Canadian climate. For this purpose, 12 projects led by teams across Canada were given funding of $50,000 to help build their prototypes, which incorporate some of the leading technologies for renewable energy and energy efficiency, such a geothermal heat pumps, motorized blinds and overhangs, and photovoltaic panels. At the end of the project, the house consumption is monitored and the general public is invited to visit the houses, to increase awareness about energy consumption in residential buildings. In this literature review, the emphasis is put on the four homes that were built in the province of Québec and in Ottawa, as those built elsewhere in Canada might not undergo similar meteorological conditions. The objective is to outline which characteristics were used to achieve net zero energy consumption, in terms of advanced envelopes, high performance mechanical systems and renewable energy.

Inspiration, the eco-home by Minto, is a 218.5 m² EQuilibrium single-family house built in Ottawa (CHMC, 2010c). The exterior walls have a very high insulation value of RSI 7.75, obtained through a double-stud wall construction, which includes rigid insulation in between two stud structures filled with fibreglass batt insulation. The ceiling is insulated with soy-based foam and blown-in cellulose, for a value of RSI 10.56, while the foundation is insulated with extruded polystyrene to obtain a value of RSI 6.69 for the walls and RSI 2.64 for the floor slab. The window area is maximized on the south-facing wall, to benefit from the solar energy, and minimized on the north-facing one. This house uses a 3 m² water solar collector coupled with two 454 L tanks, which deliver their heat through a hydronic air handler to the forced-air heating system. A gas boiler provides a back-up if more heating and hot water is needed. Finally, a 6.2 kW array of photovoltaic panels is installed on the roof to make-up for the house's consumption.

The EQuilibrium Alstonvale project, a 2 story, 230 m² house, aims at providing the tools for a net-zero living (Candanedo, J.A. et al., 2009). The building envelope is insulated with polyurethane, which has a very high thermal resistance (about RSI 0.41 per centimeter). The walls have an insulation value of RSI 5.6, while it is of RSI 12 for the roof and RSI 4.6 for the foundation slab. Triple-glazed argon filled low-e windows account for 42 percent of the south facade area, so that the house can benefit from large passive solar gains to reduce its heating load. A multitude of solar active systems are also used to provide heat and electricity. A 8.4-kW building integrated photovoltaic-thermal (BIPV-T) array is installed on the roof; excess heat produced by the panels is collected by outside air drawn under the roof. A row of solar collectors, located higher on the roof, also heats the incoming air. Heat is then extracted of this airflow through a heat-exchanger, which feeds a hybrid-source heat pump that can also use the ground loop as a heat source. A 4500 L water tank built in concrete, contiguous to the foundation, acts as active thermal energy storage for the heat extracted from the BIPV-T system, to provide autonomy for about one day of heating needs. The radiant heating floors take hot water from this tank to distribute the heat through the whole house. Forty evacuated-tube solar collectors supply most of the domestic hot water.

The EQuilibrium EcoTerra home is a prefabricated modular single-family house (CMHC, 2010a). It uses a wall system of its own, the EcoTerra Wall, which is made with regular 2” per 6” wood studs and insulated with a mix of low and medium density polyurethane foam. The medium density foam also acts as a vapour barrier. The resulting insulating value is RSI 6.69 for the walls and RSI 6.34 for the roof, while the foundation walls and floor are insulated at RSI 2.6 and 1.3, respectively. As other houses from the Equilibrium initiative, EcoTerra takes advantage of solar passive gains through well-positioned triple-glazed fenestration. The heating needs are met by the ground-source heat pump, and warm air is then distributed by the ducts to each room. A 3-kW BIPV-T system on the roof provides electricity, and excess heat is collected by air under the roof to be used for the clothes dryer and to store heat in the basement concrete floor, which has channels in it for the airflow to pass.

Abondance Montréal: Le Soleil is an urban multi-family residential building which includes three 79.3 m² units and is also part of the EQuilibrium demonstration projects (Canada Mortgage and Housing Corporation, 2011a). Each unit occupies one story, while the basement is used as a mechanical room, and a shared terrace is built on the roof. In this case, the potential for passive solar gains was less than for other projects, as the urban environment (including a 4-story building south of Abondance) does not allow for as much access to the sun's rays. However, the roof still offers an opportunity for solar energy, which the 13.8 kW photovoltaic array takes advantage of. The modules are placed on an inclined mount placed on the flat roof, to optimize the incident solar radiation. A 17.3 m^2 solar collector is also located on the rooftop to supply most of the domestic hot water needed by the three units. Heating is provided by three ground-source heat pumps (GSHP), which heat incoming air for the distribution ducts. A 5-kW electric back-up coil is also used in case of extreme cold or GSHP malfunction. To minimize the heating needs, walls and roof were insulated at respectively RSI 7.04 and RSI 12.32, using spray applied polyurethane made from soy and 40% recycled plastic.

2.1.2. LEED Platine residential buildings

While the EQuilibrium initiative has led to the construction of very energy-efficient houses that have contributed greatly to the advancement of research in this field, some private projects are also worth mentioning. In this section, attention is given to some of the first LEED Platine residential buildings in the provinces of Québec and Ontario. Those buildings are energy efficient, while also focussing on the environmental impact of materials and site used. This makes them especially relevant to this thesis, as a life-cycle perspective is adopted. It is to be noted that, even though several houses have received or are in the process of receiving a LEED Platine certification at the time of writing, the author chose to focus on three homes which she found most interesting.

Maison Écohabitation was designed and built by a team led by Écohabitation, the only firm that can deliver the LEED certification in Québec. It was meant to be an example of what can be achieved through LEED Platine certification for houses (Écohabitation, N/A). Indeed, it is one of the very few projects that have obtained a rating of more than 100 points on a possible total of

130 (Boulze, 2007). The building includes 2 units on 3 stories, additionally to an intensive green roof used to grow vegetables. Walls and roof are insulated with a mix of soy-based polyurethane and cellulose, to reach values of RSI 5.28 and RSI 8.80, respectively. Windows are all Energy Star certified, and Solatubes are installed to use natural light in darker spaces of the house during the day. Heating is provided by a ground-source heat pump and a forced air distribution system, which can also cool the house during summertime.

BL Écoconstruction has built its own LEED Platine model-house while minimizing the complexity of mechanical systems (BL Écoconstruction, N/A). The envelope consists of double-stud walls, made with 2x3 and 2x4 wood studs, and is insulated with cellulose and expanded polystyrene. The insulation values are RSI 7.04 for the walls, RSI 10.56 for the roof and RSI 3.96 for the foundation. An air solar collector preheats incoming fresh air, while a solar water heater with vacuum tubes are used to provide domestic hot water and part of the hot water for the radiant floor heating.

The VertDesign's Rideau Residence is distinguished by the fact that it is not only a LEED Platine building, but also the very first building to achieve the PassivHaus standard in Canada (Defendorf, 2011). The 2 unit, 274 m² construction has reached this standard by lowering its infiltration rate below 0.6 ACH at 50 Pa and by annually consuming less than 15 kWhr/m² for heating purposes. Heating is provided by a ground source heat pump coupled with hydronic radiant floors. The envelope is insulated with a mix of polyisocyanurate rigid insulation and closed-cell polyurethane spray foam, and prefabricated wall-panel modules were used for exterior walls. The walls have a RSI value of 7.57. To limit the environmental impact of the new construction, 95 percent of the pre-existing house were re-used or recycled. The roof is green, with 12 inches of soil on it, and plumbing and wiring are already in place for the future addition of photovoltaic modules and solar water collectors.

The characteristics of each of these houses, and other EQuilibrium projects, are compared in Appendix A.

The first section of this literature review shows that new technologies and incentive programs have made it possible to construct houses that consume very little energy. In most cases, these house also present other environmentally friendly features.

However, some of them come with a very thick, high thermal resistance envelope, while in other cases advanced HVAC systems are installed, or renewable energies meet the needs of the owners. In some cases, the published information does not indicate if optimal design alternatives were selected. An optimal solution would have to include economical considerations, in order to appeal to most home buyers, rather than just extremely environment conscious ones, therefore having more potential to make an impact on the national energy consumption. The LEED rating system, used in numerous presented houses, takes into account many environmental burdens, such as water consumption and energy usage. Nevertheless, the LEED score, although it is driven by market forces, is not an indication of the total resource consumption of a house, and is a general rating that is not adapted to each climate and region specificities.

For those reasons, the author suggests to adopt a rational design methodology that consider the long-term impact of the design choices on both the environment and the home owner's finances: a life cycle analysis.

2.2. Relevance of a life cycle approach in buildings

In the past few decades, scientists and professionals in the building industry have come to realize the importance of considering the whole life cycle when evaluating the impact of residential constructions. Of course, many of the costs associated with home ownership (like maintenance and utilities) are spread over the life of the house, so life cycle cost is a very commonly used metric in performance evaluation. However, some other impacts are traditionally taken into account only for one phase of the life cycle; that is the case for energy use, which is assumed to be significant only during the operation phase of the house (that is, for heating, cooling, ventilation, lighting and appliances). Despite this, many studies have proven that other impacts, such as energy consumption, are significant for the production and end-of-life phases, even when compared to the energy used to operate the house, and should be considered from a life cycle point of view (Itard, 2007, Dixit et al., 2010).

As buildings tend to have lower heating and cooling needs, the embodied energy represents a larger portion of the life cycle energy, sometimes as much as 30 to 60 percent (Gustavsson and Joelsson 2010, Dodoo et al. 2011). Embodied energy in low energy buildings also has a more significant contribution to total life cycle greenhouse gases emissions (Sharma et al. 2011). Furthermore, evaluating energy savings only for the operation phase of the building's life can be deceiving, as the savings might not be as significant when put in a life cycle perspective (Blengini and Di Carlo, 2010). For those reasons, it is necessary to include life cycle analysis in the optimization process for high performance buildings. The following section looks at the methodology used in a life cycle analysis.

2.2.1. Life cycle analysis methodology

Life cycle energy use is expressed in terms of primary energy. Primary energy is defined as the total energy needed to provide a final product or service (Gustavsson and Joelsson, 2010). That energy includes all losses from extraction, transformation and distribution (Sartori and Hestnes, 2007). In the case of the LCE analysis of a house, LCE of all materials (refered to as embodied energy) is usually added to the operation energy required for some of the following tasks: space heating and cooling, domestic hot water, lighting and electric appliances. Which of the energy usage are included depends on each study: for example, it might not be relevant to include appliances energy use if the main focus is the insulation of the envelope, and the appliances do not vary from a design alternative to another. Differences in interpretation and other obstacles in collecting accurate life cycle primary energy use data for buildings are further discussed in Chapter 4.

Life cycle energy analysis is part of a greater process named life cycle assessment, while life cycle costing is a parallel process. Figure 2.1 shows the steps in the life cycle assessment procedure, as defined by the international standard ISO 14040:2006 (International Organization for Standardization, 2006).

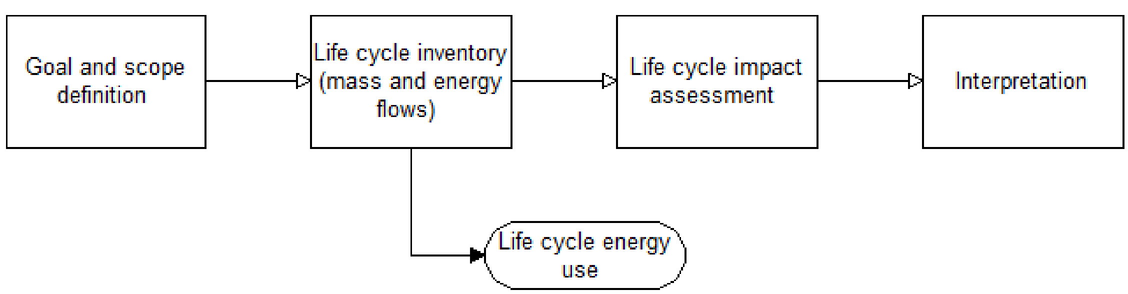

Figure 2.1 – Life cycle assessment process

In the literature, life cycle assessment (LCA) is defined as “a process whereby the material and energy flows of a system are quantified and evaluated” (Ramesh et al., 2010). Goal and scope definition is the setup of the problem, and includes, amongst other information, what metric are going to be studied, the limits of the system and the audience to which the results of the LCA are aimed. Life cycle inventory (LCI) is a critical part of LCA, as it is the step in which all the data concerning the resource, emissions and energy flows from and to the system are gathered. Life cycle assessment is the classification of LCI flows into impact categories and characterization into equivalent units (Trusty, 2010a). Impact measures can be of two natures: either mid-point or end-point. Mid-point measures involve an environmental loading, like acidification potential or green house gases emission. End-point measures aim at quantifying ultimate effects on human or ecosystem health; this proves to be more difficult and scientists do not, as of now, have a consensus on the methodology to follow in this case. Life cycle energy is not a measure of LCIA, but more of an addition of data from LCI (Trusty, 2010b), since in the LCI, phase the flows of materials and energy are determined. While LCE does not account for direct impacts on the environment, many studies have stated that energy is closely linked to environmental depletion (Dincer and Rosen, 1999, Scheuer et al., 2003, Dakwale et al., 2011), and therefore LCE is an interesting metric for life cycle optimization.

Specific primary energy use data is usually extracted from recognized life cycle inventory databases. Because the applicability of the data is highly location dependant (for example, the electricity mix used for the production of a good has a large impact on the efficiency of energy conversion, and therefore, on the primary energy use), it is preferable to use a database specific to the area studied. LCI databases are often included as part of a complete LCA tool. Bribían et al. (2009) have listed the main tools available both for general and building related LCA. In Canada, the most common tool is the Athena Impact Estimator (Athena Institute for Sustainable

Materials, 2008), which is used in practically all studies that analyse life cycle energy (Kassab, 2002, Yang and Zmeureanu, 2008, Frenette et al., 2010, Leckner and Zmeureanu, 2011, Van Ooteghem and Xu, 2012.) The most commonly used tool for the rest of North America is SimaPro, but it does include data adapted for Canada (PRé, N/A).

2.3. Life cycle analyses and optimizations of residential buildings

Many studies have presented life cycle analysis of buildings and their systems. Such works, even if they usually are specific to a given area or climate, give guidelines that can be used for future design projects. The following paragraphs outline life cycle analyses conducted on energy systems and house envelopes, presenting their criteria, methodology and conclusions. The first section is dedicated to comparative analyses, and the second one, to life cycle optimizations.

2.3.1. Comparative life cycle analyses

Depending on whether the mechanical systems or building envelope is being analyzed, "life cycle" can be interpreted differently. Indeed, in the case of mechanical systems, sometimes only the operation phase of the equipment is considered, meaning the energy resources consumed to heat, cool, ventilate or light a building. To evaluate the life cycle impacts, the analyst then has to take into account the life cycle of the resource (e.g. natural gas) being used, from its extraction to its transport and combustion. That type of analysis was conducted by Zmeureanu and Wu (2007) for different heating systems with and without separate mechanical ventilation through life cycle energy, exergy destruction and GHG emissions. The reason why the embodied energy of mechanical systems is sometimes neglected is two-fold: on one hand, the mass of appliances, including HVAC equipement, is estimated to be small (only 1.5% of the total mass of the house, according to Keolian et al., 2001), while the composition of these objects is hard to determine and generally not included in building LCI databases. Despite this added difficulty, some studies have considered both the life cycle impacts of HVAC production and operation.

Yang (2005) compared the life cycle impacts of forced-air and hot water with ventilation heating systems in Montreal, using energy, cost, exergy destruction and GHG emissions. In this study, electricity, gas and oil are considered for energy sources. The energy consumption is based on a comprehensive design of each system and is evaluated with the Engineering Equation Solver (EES). To mitigate the lack of reliable information concerning materials included in the manufacturing of HVAC equipment like boilers and furnaces, decision models with uncertainty are employed, which includes a payoff matrix to analyze the various design alternatives. It is found that the contribution of heating systems to the impacts in the pre-operating phase is between 1.4 and 6.7% with respect with the complete house, depending on the selected system. It also identifies that an electric hot water system has the lowest GHG emissions, a gas hot water system has the lowest energy consumption and exergy destruction and an electric forced air system has the lowest cost for Montreal.

An extensive evaluation of heating production and supply systems was done by Alanne et al. (2007) for the Nordic climate of Helsinki. Ten combinations of heat production and supply equipments are suggested, including “district heating, geothermal heating, electrical heating applying baseboards, floor heating or auxiliary heat sources (fireplace, solar heating, air heat pump), oil heating (with or without solar heat collectors), [...] traditional natural gas heating” and a micro-cogeneration system (micro-CHP), with the focus being on comparing the micro-CHP to other systems. This research accounts for the high proportion of uncertainties in life cycle assessment using the Preference Assessment by Imprecise Ratio Statements method. The comparison is conducted through a weighted sum, giving weights value to each of the three criteria: life cycle cost, life cycle environmental burden due to emissions and life cycle environmental burden due to natural resource consumption. This yields the conclusion that micro-CHP is superior to the district heating, electrical heating, oil heating and natural gas heating without electricity generation.

Shah et al. (2008) compared the life cycle impacts of three heating and cooling systems over a period of 35 years in four different states in the U.S. The systems considered were warm-air furnace and air-conditioner, hot water boiler and air conditioner, and air–air heat pump. It was found that because of the different electricity mixes and climates, the air-source heat pump would have the highest impacts in Minnesota, Pennsylvania and Texas, while it would have the least impacts in Oregon.

Saner et al. (2010) employed LCA to estimate the environmental benefits and disadvantages of using a ground source heat pump as a heating system. The life cycle assessment methodology was used to obtain the relative contribution of various types of environmental damages (ie. resource depletion, human health, etc.) to the total environmental impact. It was also shown that for a life cycle of 20 years, a GSHP heating system in continental Europe saves between 31% and 88% in equivalent CO2 compared to oil fired boilers and gas furnaces, depending on the electricity mix.

Leckner and Zmeureanu (2011) conducted a life cycle analysis of energy and cost for a net-zero energy house (NZEH) with a solar combisystem (providing both heating and hot water) in Montréal. A TRNSYS model was built to evaluate the operation energy consumption. Some of the main findings were that the energy payback of this type of system is between 8.4 and 8.7 years, and that financial payback is never achieved due to low energy prices and high investment costs. The incremental changes to a base case house (typical Canadian construction) to make it net-zero energy were also studied. As mentioned by other studies, it show that it is most cost-effective to reduce energy demand by adding insulation, improving the thermal properties of windows (from double to triple pane) and using energy efficient appliances and lighting.

Chiavetta et al. (2012) used LCA to compare two renewable energy heating systems: a thermosyphon solar thermal system and a ground-source heat pump, for a house in Bologna, Italy. A cradle-to-grave LCA showed that the ground-source heat pump has less environmental impacts that the solar system.

Greening and Azapagic (2012) also used LCA to compare the environmental impact of different types of heat pumps (air-source, ground-source and water-source) to that of a natural gas boiler, for United Kingdom. They used manufacturer data to estimate the material inventory by mass for each heat pump. Because electricity generation in the UK has very high embodied emissions, all types of heat pumps have higher overall impact than a natural gas boiler, which contrasts with the assessment of Saner for continental Europe. However, some specific impacts (global warming, fossil resource depletion and summer smog impacts) are smaller for heat pumps.

Similar methodologies have been applied to envelopes. Keolian et al. (2001) conducted a LCE, LCC and LCGHGE assessment for a single-family house in Michigan, United States. They compare those life cycle metrics for both a base case house and a energy efficient house, for which 11 energy efficiency strategies were applied (including high performance windows, energy efficient lighting, increased insulation, etc.). Four energy price scenarios were considered for a life cycle period of 50 years. While a reduction of LCE of about 60% was achieved, the payback period for the energy efficiency strategies was about 50 years.

Kassab (2002) used a parametric analysis to compare the effects of operation conditions and envelope and architectural design on energy performance, and then chose 89 design alternatives by combining design features in different ways, to conduct a life cycle analysis that included energy, cost and global warming potential (GWP). The author proposes a decision system in which each of these alternatives' score is normalized and the best scenario is chosen with a weighted sum to include all three criteria. The preferred alternative varies greatly depending on the value given to each of the criteria.

Baouendi et al. (2005) proposed a tool that can evaluate LCE, LCGHGE and LCC for a house, by incorporating the following tools: HOT2000 for the energy consumption, ATHENA Impact Estimator for the embodied energy and emissions and RS Means for the construction costs. A case study shows the results for an existing house in Montreal, Quebec, as well as for four alternative constructions for walls, roof and basement. It is show that reductions in LCE and LCGHGE lead to an increased LCC for the proposed construction alternatives.

Zmeureanu et al. (2005) then used this tool to evaluate different levels of insulation and corresponding wall wood stud structure for these three metrics, for the same base case house in Montreal. Four insulation materials were considered and it was concluded that polystyrene is not effective from either a LCC or LCGHGE, mostly because of low electricity prices in Quebec and because this electricity is produced with hydraulic power, which yields negligible GHG emissions. The optimal level of insulation from a LCC perspective is between a 2"x8" and a 2"x10" wood stud, and sprayed cellulose leads to the lowest LCC, closely follow by mineral fiber and fibreglass.

Gustavsson and Joelsson (2010) have analyzed the life cycle primary energy use and CO_2 emissions of low energy and conventional buildings in Sweden. Five case study buildings, including single-family houses, row houses and multi-units dwellings, were selected and a LCA was conducted on each of them, including all life phases except on-site construction, demolition and renovation. Several variations were added to each of the buildings, to compare conventional construction with passive construction, wood framing with concrete, multiple heat supply systems and insulation levels. Life-cycle inventory data was gathered from various sources in the literature and previous studies. Wood-framed houses proved to require less energy when compared to an identical concrete construction. It was shown that low-energy buildings have a higher primary energy use for production than conventional buildings; for some houses, the production primary energy use could even reach up to 60% of the total life-cycle use. However, the life cycle energy savings caused by added insulation were ten times greater than the additional embodied energy in the insulation materials. Another major finding was that heat supply systems had a greater impact on energy consumption than energy-efficiency envelope measures. The lowest LCE heat supply systems were heat pumps and cogenerated district heating, but biomass was better at lowering CO_2 emissions.

Hugo and Zmeureanu (2012) studied the LCE and LCC for improvements to the envelope energy efficiency and for a solar combisystem with seasonal thermal storage. It showed that solar combisystem are not cost-effective in the current conditions for Montreal, Canada, and that improvements to the envelope are a better choice from a cost perspective.

Life cycle cost is a particularly popular metric in life cycle analysis because it encompasses in a way the energy needed for production and operation of the building. A high energy consumption will result in a higher asking price for a product, and operation energy will translate into higher utility bills.

Saari et al. 2012 evaluated the LCC of eight energy saving concepts for a detached house in Finland. Energy saving concepts included increased insulation or air tightness, and heating systems, such as electrical floor heating, ASHP, GSHP and solar water heating. ASHP was found as being the strategy that has the lowest payback period, while it was concluded that thick insulation was not attractive from an economic perspective.

Kegel et al. (2012) calculated the LCC for four heat pump systems (ASHP, cold climate ASHP, GSHP and solar assisted ASHP) for a detached house in the Toronto area, which had three possible levels of insulation (a typical 1980’s house, a house with an EnerGuide Rating Scale (ERS) of 80, and a “net zero ready” house), and two possible natural gas price scenarios. For the 1980’s house, the lowest LCC option was the ASHP, while the GSHP was better for “net zero energy ready house”. For the ERS-80 house, the best system between the ASHP and GSHP depended on the natural gas price scenario, because the back-up for ASHP is a natural gas furnace.

Georges et al. (2012) looked at interactions of envelope and mechanical systems in the design of an optimal detached house from an economic and environmental perspective. The total primary energy consumption, equivalent CO2 emission and life cycle cost were analyzed for combinations of five levels of envelope insulation (from code compliant to Passivhaus standard) and 16 mechanical systems for a house in Belgium. The least energy efficient systems, such as the electric baseboards, became cost effective when the envelope was insulated in a way that space heating needs were extremely low (ie. meeting the PassivHaus standards). However, the PassivHaus envelope was only cost effective if very severe economic assumptions were made (namely a low discount rate and a high energy price escalation rate).

2.3.2. Optimization cases

To consider at a wider array of design possibilities, optimization algorithms are more suitable. They also allow for the study of interactions between design variables, contrary to parametric studies, as pointed out by Bichiou and Krarti (2011). Most life cycle optimization works rely on the combination of a modeling program, which assess either the annual heating and cooling loads of the envelope or the energy consumption of the HVAC systems in the building, and an optimization program, which uses algorithms to modify the value of input parameters in the simulation program and converge towards the minimal cost function. This is the case of the three following studies.

Djuric et al. (2007) conducted a life cycle cost optimization of a school building in Belgrade, but added thermal comfort as a constraint, evaluated through the Predicted Percentage of Dissatisfied (PPD). The variables considered were insulation level, supply temperature to heating system and area of radiators. The simulation software Energy Plus was chosen, coupled to GenOpt for the optimization, using a hybrid PSO-Hook-Jeeves algorithm.

Hasan et al. (2008) conducted an optimization study to minimize the life cycle cost of a single-family Finnish house. Variables taken in consideration included the envelope design and heat recovery system, and were either discrete or continuous. The chosen modeling software was IDA Indoor Climate and Energy 3.0, a program released in 2001 by a team of Scandinavian researchers to assess thermal comfort, indoor air quality and energy consumption in buildings (EQUA, 2002). It was coupled to GenOpt 2.0, which used a hybrid Particle Swarm and Hooke-Jeeves optimization algorithm. The research concluded that higher insulation values were only helpful when energy price escalation was high, mainly because of the high investment cost of the considered insulation (polyurethane).

A life cycle cost optimization with respect of the envelope shape, window ratio, infiltration rate and insulation level has been performed by Tuhus-Dubrow and Krarti (2010) for five different climates in the United States. DOE-2, the simulation program developed by the U.S. Department of Energy, was used to obtain the operation energy needed by the building. A genetic algorithm was implemented in Matlab and in Perl to optimize the variables. For the coldest climate (Boulder, Colorado), it was found that the optimal life cycle cost is reached with a square building with wall insulation of R-21 (RSI 3.70), ceiling insulation of R-30 (RSI 5.28) and typical infiltration level, which is rather low compared to other life cycle optimizations.

The work of Bichiou and Krarti (2011) aims at minimizing LCC for both envelope and mechanical systems in five American cities while evaluating the performance of optimization algorithms for this task. Various design variables are taken into account: shape, orientation, insulation, thermal mass, as well as many mechanical systems (furnace, electrical resistance, ground-source heat pump). Separate optimizations for the envelope and mechanical systems were conducted, and then compared to an optimization of both components at once. It was found that optimizing both simultaneously yields slightly more accurate results. The full optimization showed that in cold climates, either a furnace (Boulder, Colorado) or a vertical GSHP (Chicago, Illinois), was the best alternative.

The studies mentioned above aimed at optimizing a single objective. While Djuric et al. took into consideration a second objective for the optimization, it was only in the form of a constraint. Other research works have treated the subject of trade-offs between multiple objectives in building optimization. In this part of the literature review, previous studies on multi-objective optimization for cost and environment are presented.

Wang et al. (2005) presented an optimization for the envelope shape and thermal properties for an office building in Montreal, meant to help green building designers at a conceptual stage. The two objectives were life cycle cost and life cycle exergy consumption, which was chosen as an environmental indicator. A genetic algorithm was applied to obtain a Pareto front of solutions, which gives the optimal solutions for numerous different weighted values of the two objectives. It was found that some variables, such as window-to-wall ratio, remained constant for all Pareto solutions, while others varied greatly depending on the zone where they were located on the Pareto front.

Verbeek and Hens (2007) conducted a comprehensive optimization study with the objectives of minimizing life cycle cost, energy and global warming potential (as an indicator of environment depletion) for extremely-low energy buildings in Brussels, Belgium. The envelope features were optimized first, independently of the HVAC system, because it was considered that the envelope design has long lasting impacts on the energy performance and that it is more appropriate to design heating systems suitable for the very low energy consumption of the said envelope. This optimization was also performed using a genetic algorithm with Pareto front, implemented through Matlab. It concluded that there is no reason for concerns about embodied energy of energy saving measures such as additional insulation, because it usually has an energy payback time of less than 2 years. It identified district heating systems as being the most efficient in terms of energy, GWP and cost, followed by heat pumps.

Hamdy et al. (2010) proposed a multi-stage, multi-objective optimization for a near net zero energy, single-family house in Finland. First, they looked at the envelope and heat-recovery systems, and in a second phase, at the heating and cooling systems. The final stage of the optimization looked at improving the mechanical systems by adding solar energy components. It was concluded that investing in a energy efficient heating system has a better financial and environmental viability than high insulation. For a wide range of escalation range values, it was found that the ground-source heat pump was the optimal heating system, for a multi-criteria optimization of primary energy consumption and life cycle cost. Furthermore, it was proven that financial and environmental aims do not have to contradict each other, as the primary energy consumption of the cost optimal solution was 47% below that of a code compliant house.

2.4. Conclusions on the state of green building design

This chapter presented a small sample of the most advanced of many green residential buildings that were recently built in Canada. These buildings make use of a wide variety of technologies to achieve very low or net zero energy consumption. Additionally, while designers often show that they are sensitive to potential environmental impacts, it is not clear that a systematic methodology was used to minimize them. Therefore, using LCA to design a low-energy house that is adapted to Southern Quebec conditions would be interesting to establish a case study that truly addresses environmental challenges. Furthermore, all net zero energy houses presented here are demonstration projects, and are not cost effective because of their very high investment cost (Carver et al., 2012). Consequently, it would make sense to also optimize life cycle cost in order to make green buildings available to a larger part of the population.

A survey of LCA methodology and tools has shown that tools are available to conduct a full LCA procedure on Canadian buildings, from the definition of goals and scope to the interpretation of environmental impacts; the Athena Impact Estimator is the tool that is widely used in Canada for that purpose. However, some materials are not covered in Athena databases, and completing the work to obtain a full LCA of a green building might be tedious. Because of the complexity of LCA, many other studies have turned to the analysis of LCE and LCGHGE, which are obtained from the life cycle inventory phase of LCA. Indeed, many have shown that energy use is closely linked to environmental depletion. LCC is also often coupled to LCE and LCGHGE analysis, because, in reality, cost is frequently the first criterion for decision makers.

Two main types of life cycle studies were found in the literature: comparative life cycle analyses and life cycle optimizations. The main difference is that optimizations use algorithms to evaluate a very large number of configurations within their search domain. LCA is more likely to be used in comparative studies, because of the great quantity of results to be processed (Shah et al., 2008, Saner et al., 2010, Chiavetta et al., 2012). For most optimization processes, an energy simulation software (such as TRNSYS, Energy Plus or IDA ICE) is coupled to a program that manages the optimization algorithm. While genetic algorithms are usually implemented by a mathematical language program (like Matlab), GenOpt is widely used for other algorithms. Most optimization works presented were for a single objective. For multi-objective optimizations (like Wang et al., 2005, Verbeeck and Hens, 2007, Hamdy et al, 2010), genetic algorithms are especially useful for multi-objective optimizations because they can find the Pareto front, which represents the optimal solutions for a variety of weight ratio for objectives. The optimization of mechanical systems is usually decoupled from the envelope because, as HVAC sizing is affected by the design of the envelope, it is rather complex to build a model that automatically resizes mechanical components depending on the envelope optimization results, although some have achieved it (Bichiou and Krarti, 2011).

Based on life cycle analyses and optimizations, some heating systems have been identified as having an low energy consumption as well as a limited environmental footprint, or an interesting life cycle cost. It was also generally agreed that increasing the insulation level and improving the quality of windows was a cost-effective way of reducing energy use, even when considering the added embodied energy due to greater use of material (Zmeureanu et al., 2005, Verbeeck and Hens, 2007, Gustavsson and Joelsson, 2010 and Leckner and Zmeureanu, 2011). However, the high cost of some insulation materials, like polyurethane or polystyrene, may be prohibitive when life cycle cost is considered (Zmeureanu et al., 2005, Hasan et al, 2008), or when material and energy prices are not favorable (Saari et al., 2012). Furthermore, while insulation does payback financially and environmentally, some other studies show that mechanical systems have a greater impact on energy consumption or a more interesting return on investment (Gustavsson and Joelsson, 2010, Hamdy et al, 2010). ASHP was generally seen as a cost effective (Saari et al., 2012, Kegel et al., 2012), while GSHP is often the best system from an environmental point of view (Saner et al., 2010, Bichiou and Krarti, 2011, Chiavetta et al., 2012), except when the electricity mix used comes from a polluting source (Shah et al., 2008). Many studies that used more than one criterion pointed out that the optimal solution varied greatly depending on the criterion used (Keoleian et al., 2001, Kassab, 2002, Baouendi et al., 2005, Yang et al., 2005). Some studies that accounted for uncertainties in the data said that no clear dominance could be established between the mechanical systems (Alanne et al., 2007).

The current number of studies of life cycle analysis and optimization might not be sufficient to help a green building designer to make the right choices for the envelope and HVAC systems of a residential building for a given geographical area. More specifically, there has not been a complete optimization of both envelope and mechanical system components for the specific conditions of Southern Quebec. Gustavsson and Joelsson (2010) have also pointed out that more life cycle analysis of low-energy buildings are needed. Finally, Kassab (2002) also concluded that more efforts were “required to evaluate the impact of the entire building systems on the energy-efficient design”. This consensus reinforces the relevancy of this thesis, which aims at optimizing the life cycle of a residential building envelope and HVAC systems for the cold climate of Québec.

In the next chapters, the methodology to find the optimal combination of house envelope and mechanical systems for the specific conditions of Ste-Agathe-des-Monts, Quebec, is developed. Chapter 3 presents the modeling of the base case house, which allows to introduce the details of the model that remain the same over the optimization process. Chapter 4 outlines the optimization process for the house envelope, including the life cycle data and the optimization algorithm. Chapter 5 explains the detailed design and modeling of the four space conditioning systems and the three domestic hot water systems, for one optimal envelope. Chapter 6 presents the life cycle data for the mechanical systems, followed by an analysis of the life cycle performance of each combination of mechanical systems with one of the three levels of house envelope considered (code compliant, minimal life cycle cost and minimal life cycle energy).

3. Modeling of the base case house

In this chapter, the base case house, as proposed by Happy Modular, is modeled through the transient simulation program TRNSYS 16 (SEL, 2006). This model focuses solely on the building envelope features, for which a life cycle performance optimization is carried out, before moving on to the optimization of the heating, cooling and domestic hot water systems within this optimal envelope.

3.1. Description of the base case house

For the base case study of the envelope, the plans for Happy Modular's first model house are used. The house is located about 15 km east of Ste-Agathe-des-Monts (Québec). It is a two-story house made of four standard modules, with a total heated floor area (including a finished basement) of 130.4 m². One particularity of the house is that the frame is tilted by 30°, so that its roof has an angle of 30° with the horizontal, towards the south. However, the south facade, which is an entirely glazed curtain wall, has a vertical tilt. It is built out of rectangular modules of 4 m per 4 m per 8 m, and the structure of those modules is made of large structural glulam beams that are visible from the inside of the house. The wall frames are made out of 38 mm per 140 mm (2 in per 6 in) wood studs. For the purpose of this envelope modeling, no specific heating and cooling systems are added to the model. Consequently, the simulation calculates the thermal loads instead of energy consumption. Those loads are then converted to real electricity use by assuming that heating is provided by baseboard heaters with an efficiency of 100 percent and conditioned by an air-conditioning unit with a COP of 3.

3.2. Description of TRNSYS components used for modeling

The assessment of energy use as well as other valuable data such as air temperature inside the living space is conducted through the transient system simulation program TRNSYS, version 16

(SEL, 2006). TRNSYS is selected because of its great flexibility in modeling diverse energy systems (Bradley and Kümmert, 2005), ranging from domestic hot water tanks to forced-air furnaces. The software also allows for the input of building data through a dedicated visual interface (TRNBuild).

Models of all components, including the house model composed of three thermal zones, are represented in the TRNSYS Simulation Studio in the form of "Types", which have inputs and outputs that can then be connected to other components to create complete systems. Table 3.1 presents TRNSYS standard and TESS libraries (TESS, 2007) components used in the base case envelope simulation.

Table 3.1 – Types used in the TRNSYS model of the base case house

Type	Description	Name used in Simulation studio
2	Differential Controller	Heaton/Coolon
14	Time Dependent Forcing Function	Type14h
15	Weather Data Processor	Type15-3
25	Printer – No units printed to output file	Type25f
28	Simulation Summary: Results to External File, No Energy Balance	Type28b
33	Psychometrics: Dry Bulb and Relative Humidity Known	Type33e
34	Overhang and Wingwall Shading	Type34
41	Load Profile Sequencer – Unique Days of the Week	Type41c
56	Multi-Zone Building	Type56b
65	Online Graphical Plotter	Type65d
69	Effective Sky Temperature for Long-Wave Radiation Exchange	Type69b
515	Heating and Cooling Season Scheduler (TESS)	Type515
648	Air Mixing Valve with up to 100 Inlets (TESS)	Type648
701	Basement Conduction (Interfaces with Type56) (TESS)	Type701c
754	Simple Heating and Humidifying System : Temperature Controlled (TESS)	Type754f
760	Sensible Air to Air Heat Recovery with Controlled Outlet Conditions (TESS)	Type760a

The TRNSYS model can be divided in four main sections: building model, weather data processing, ventilation heat recovery and HVAC setting controls.

3.2.1. Type 56 : Multi-zone building

Type 56 is defined in TRNBuild and is used to connect the building to other TRNSYS components' inputs and outputs. TRNBuild is a user interface that allows easy definition of the building envelope, thermostat settings, internal gains and zones, and writes a file that is read by TRNSYS and can also be modified in a text editor. Windows can be chosen from a wide selection in WINLib (a window library included with the software), while envelope components (types of walls, floors, foundations and roofs) are created by assembling layers of massive or non-massive materials.

The building model is divided into three zones: the basement, the first floor and the second floor. The basement is also a living space and is therefore heated with respect to the same temperature set point as the two other floors.

The total heated floor area is 130.4 m², including a basement of 46.4 m², and the total heated volume is 524 m³. As the house has a flat roof, at a 30° tilt angle, there is no attic space. The roof has an area of 40 m² (excluding overhangs) and an exterior finish made of steel sheeting. There is a total of 58 m² of window area, and exterior doors cover an area of 3.7 m². An open staircase connects the first floor and the mezzanine; air exchange between the two zones through this opening is addressed in section 3.2.1.3.

3.2.1.1. Envelope components

The exterior above-ground walls are composed of 8 mm thick tiles of asbestos-cement, a 15 mm air layer, 25 mm of sprayed polyurethane, 11 mm OSB boards, 138 mm of cellulose insulation and 13 mm gypsum board for the interior finish, with a structure of 38 mm per 140 mm wood studs at a 700 mm spacing. The nominal thermal resistance, excluding the thermal bridges generated by the wood studs, is equal to 5.27 $m^2 \cdot K/W$. The problematic of thermal bridging for each is addressed at section 3.2.1.2.

The roof is composed of 1 mm steel sheeting, 19 mm plywood board, 223 mm of sprayed polyurethane, 15 mm air layer and 13 mm gypsum board, a structure of 38 mm per 190 mm wood studs at a 700 mm spacing. The nominal thermal resistance of is equal to 8.40 $m^2 \cdot K/W$.

Below-grade foundation walls are made of 200 mm of cast-in place concrete, with 75 mm of sprayed polyurethane on the inside and 13 mm gypsum board for the interior finish, with a structure of 38 mm per 90 mm wood studs. The nominal thermal resistance is equal to 2.87 $m^2 \cdot K/W$. The basement floor is also made of concrete, with 10 cm of sprayed polyurethane below it.

Table 3.2 presents the layers of each wall type with their thermal resistance. Their properties come from ASHRAE 2009, with the exception of cellulose insulation and sprayed polyurethane, which are taken from the manufacturers' literature (Benolec, 2012 and Demilec Canada, 2009). Internal and external convective coefficients of air layers are then added by the computer model. For still air inside the house, they correspond to 8.3 $W/m^2 \cdot K$ for walls and to 9.2 $W/m^2 \cdot K$ for flat surfaces (ceilings and floors), as per ASHRAE (2009). For the outside convection coefficient, the value suggested by TRNSYS, 17.8 $W/m^2 \cdot K$, is used.

Table 3.2 – Wall types and layers description

Wall Type	Layers	Thickness [mm]	RSI Value [m²·K/W]
Basement floor	Concrete	100	0.06
	Polyurethane	50	1.80
	Total		**1.86**
Basement wall	Gypsum	13	0.05
	Polyurethane	75	2.70
	Concrete	200	0.12
	Total		**2.87**
Exterior wall	Gypsum	13	0.05
	Cellulose insulation	138	4.00
	OSB board	11	0.08
	Polyurethane	25	0.90
	Air layer	14	0.16
	Asbestos cement	8	0.05
	Total		**5.24**
Roof	Gypsum	13	0.05
	Air layer	14	0.15
	Polyurethane	223	8.03
	Plywood	19	0.17
	Steel	1	0.00
	Total		**8.40**
Floors	Concrete	100	0.06
	Plywood	19	0.17
	Total		**0.23**

Windows are triple-pane low-e and their characteristics are outlined in Table 3.3. All of the table values are given with respect to the interior and exterior heat transfer coefficients presented at the end of the table.

Table 3.3 – Base case window properties

Number of panes	3
Low-e coating	On surfaces #2 and #5 (numbering starting at the surface on the exterior side of the house)
Glass thickness	4 mm
Gap width	16 mm
Filling gas	Argon
Center of glass u-value	0.7 W/m²·K
Center of glass g-value	0.501
Percentage area of frame	15%
Frame u-value	2.27 W/m²·K
Solar absorptance of frame	0.6
Interior heat transfer coefficient	8.3 W/m²·K
Exterior heat transfer coefficient	17.8 W/m²·K

A shading coefficient of 0.375 is defined for the windows. This corresponds to half of the windows area being covered by white roller shades (optical and thermal properties from ASHRAE 2009) at all time. This steady schedule is chosen because the roller shades are not motorized, and therefore need to be pulled down by the occupants. The occupants are unlikely to pull down the shades during the day, even if it becomes too warm, because they might not be at home. While it would be better to pull the shades down at night during the winter to avoid losing heat by radiation to the sky, it is also assumed that the occupants' behaviour might not correspond to this perfect case.

In July 2012, Quebec regulations were modified for the first time in 20 years, to reach the requirements of the previously voluntary energy efficiency program, Novo-climat. Table 3.4 gives an overview of the thermal resistance of the base case house envelope compared to the previous Quebec law, as stated in the *Règlement sur l'économie de l'énergie dans les nouveaux bâtiments* (Gouvernement du Québec, 1992), the Novoclimat program (Agence de l'efficacité énergétique, 2011), which came into effect as the new regulation in August 2012, and the Equilibrium housing demonstration projects (CMHC, 2011). Values presented here for the

Québec regulations are for climatic zone B, where Ste-Agathe-des-Monts is located. Equilibrium housing demonstration projects are an initiative of the Canada Mortgage and Housing Corporation; only values for the three single-family houses built in Eastman (Québec), Hudson (Québec) and Ottawa (Ontario) were considered in this table to compare similar houses in similar environmental conditions. The thermal resistances in the following table are based solely on conductive resistances, as all convective heat transfer coefficients are not considered in regulations.

Table 3.4 – Base case house characteristics versus recommended values

Thermal resistance of the envelope [m²·K/W]	Happy Modular	Previous Quebec regulations	Novoclimat	EQuilibrium housing projects
Ceiling/roof	8.40	5.6	7.22	6.34 - 11.45
Above-ground walls	5.24	3.6	4.31	5.37 - 7.75
Foundation walls	2.87	2.2	2.99	5.28 - 6.69
Basement floor	1.86	-	0.88	1.23 - 2.64
Exterior doors	1.37	0.7	Polyurethane insulation	N/A
Windows	1.05	0.35	Double-glazing argon and low-e	0.7 - 1.2

3.2.1.2. <u>Thermal bridging</u>

Because thermal bridges can cause as much as a 50 percent increase in nominal thermal transmittance of walls (Roos & Gorgolewski 2011), they are modelled based on the parallel heat flow paths method, as prescribed in the Handbook of Fundamentals 2009 (ASHRAE 2009). To do so, each wall is modelled as a combination of two walls totalling its equivalent area: one with a layer of cavity insulation and one with a layer of wood that creates the thermal bridge. A framing factor of 0.22 or 0.18 (ASHRAE 2009), which represents the portion of the wall area that is composed of a thermal bridge (wood stud or header), is used respectively for single-stud walls and roof. This calculation method is intended to be used for steady-state heat transfer, while

TRNSYS performs transient analyses. Minor losses of accuracy are expected, but are nevertheless acceptable as this representation constitutes a significant improvement over not considering thermal bridges. A 2D or 3D transient model of the envelope is beyond the purpose of this study because of the large computing time that would be required for the optimization.

3.2.1.3. Geometry

Figures 3.1 and 3.2 show the rendering of the model house.

Figure 3.1 – Rendering of the model house’s profile (Courtesy of Gau Designs & Concepts)

Figure 3.2 – Rendering of the model house's facade (Courtesy of Gau Designs & Concepts)

The base case is modelled with its glazed facade facing due south. Table 3.5 presents the area of external walls, roof and windows for each cardinal orientation. The walls area includes windows area. It is also to be noted that half the basement walls area is assumed to be underground while the other half is in contact with the outside environment.

Table 3.5 – Dimension of the external envelope

Orientation	**Slope**	**Level**	**Area [Walls/windows] (m^2)**
South	90° (with respect to the floor)	Basement	22.64 / 0.35
		First floor	26.40 / 26.00
		Second floor	20.71 / 19.41
East	90°	Basement	16.42 / 0.35
		First floor	24.78 / 3.29
		Second floor	24.43 / 2.61
North	60°	Basement	22.64 / 0.35
		First floor	40.54 / 0.00
		Second floor	47.26 / 0.00
West	90°	Basement	16.42 / 0.35
		First floor	24.78 / 3.29
		Second floor	24.43 / 2.61
Roof	-30°	-	40.45 / 0.00

3.2.1.4. Airflow between zones

The mezzanine on the second floor is represented by a 58.7 m² floor with a 21.2 m² glazing-free opening through which an airflow is coupled with the first floor. Work by Vera and al. (2010) has concluded that airflow through a horizontal opening is “mainly driven by buoyancy and may be considered as natural convection” when the ventilation rate is under 0.5 ACH. Since the ventilation rate in both the first and second floor is equivalent to 0.24 ACH (see section 3.2.3 for further details), an empirical equation developed by Peppes (Peppes and al., 2002) is used to estimate the balanced flow rate between the two floors, m_{conv} [kg/hr], depending on the average air temperature difference between them:

$$m_{conv} = a \cdot A \cdot \sqrt{gH} \cdot \left(\frac{\max(0.01, T_1 - T_2)}{\frac{T_1 + T_2}{2}} \right)^{0.3} \quad \text{(Eq. 3.1)}$$

where *a* is the conversion factor to obtain an *A* is the area of the horizontal opening in m², *g* is the gravitational acceleration in m/s², *H* is the thickness of the partition between the two zones in m, T_1 is the average air temperature of the first floor and T_2, of the second floor, in K. This equation is implemented in the equation block *Vol_conv*, which receives input and send outputs with Type 56. The flow rate varies between 1,300 kg/hr and 6,640 kg/hr over the year.

3.2.1.5. Air infiltration

Infiltration of outdoor air is estimated constant throughout the year according to Sherman's model (Sherman, 1987). This model takes into account the climate, the number of stories of the house, the shielding of the building and the size of cracks that allow air to penetrate inside to calculate a correlation factor. The air change per hour (ACH) at 50 Pa value is then divided by this correlation factor *N* to obtain the ACH value under operating conditions:

$$N = N_0 \cdot H_N \cdot S_N \cdot L_N \quad \text{(Eq. 3.2)}$$

where N_0 is the leakage-infiltration ratio (depending on the geographical zone in the USA or Canada), and H_N, S_N and L_N are corrections factors, respectively for the height, shielding and leakiness of the building. The average N_0 for the zone in which Ste-Agathe-des-Monts is located is taken (18.5), H_N is chosen for a two-story building, shielding is considered «normal» and leakiness correction factor is taken for small cracks, as this building will be very air-tight compared to building code standards. This yields a value for N of 20.72.

The air change rate at 50 Pa is assumed to be 1 ACH, which is attainable when compared to other low energy houses (from CHMC Equilibrium initiative: EcoTerra 1.0 ACH, Riverdale 0.5

ACH, Inspiration Minto 0.65 ACH, (CHMC, 2011)). When divided by the correlation factor, this translates to an ACH value of 0.048 under operation conditions.

3.2.1.6. Internal gains

Internal gains coming from the three adult occupants are defined through an occupancy schedule as follow: vacancy from 8:00 to 17:00 during the week, and from 12:00 to 16:00 on weekends. When the occupants are home, they are assumed to be seated and working lightly, which is equivalent to a heat gain of 150 W, according to ISO 7730 standard, with an average of one person per floor.

Artificial lighting intensity is set to 1.25 W/m² with compact fluorescent lighting (CFL), which is equivalent to a standard 5 W/m² for incandescent lighting, considering that CFL is 75% more efficient. Artificial lighting is turned on only when occupants are in the house. According to ASHRAE Handbook of Fundamentals 2005 (ASHRAE, 2005) p. 30.22 table 16, heat gains from CFL are 67% radiative and 33% convective.

When the house is occupied, it is assumed that a personal computer (140 W) is being used on the second floor, and a television on the first floor (80 W).

3.2.1.7. Humidity control

A humidifying and dehumidifying feature is included in the TRNBuild model. The humidification process is added to the heating type, in order to prevent the relative humidity level to go below 30 percents, according to good practices in a cold Canadian climate (Canada Housing and Mortgage Corporation, 2009). Dehumidification is added to the cooling type in order not to exceed a relative humidity of 65%, which corresponds to the ASHRAE Standard 55-2010 of 0.012 humidity ratio at 24°C (the cooling temperature set point).

3.2.1.8. Type 28b: Simulation Summary: Results to External File, No Energy Balance

In TRNSYS Simulation Studio, Type 28b is added to obtain the yearly heating and cooling load by numerically integrating the instantaneous heating and cooling power for every simulation step.

3.2.2. Weather data processing

Figure 3.3 presents the interconnections between Types for the weather data processing portion of the TRNSYS model.

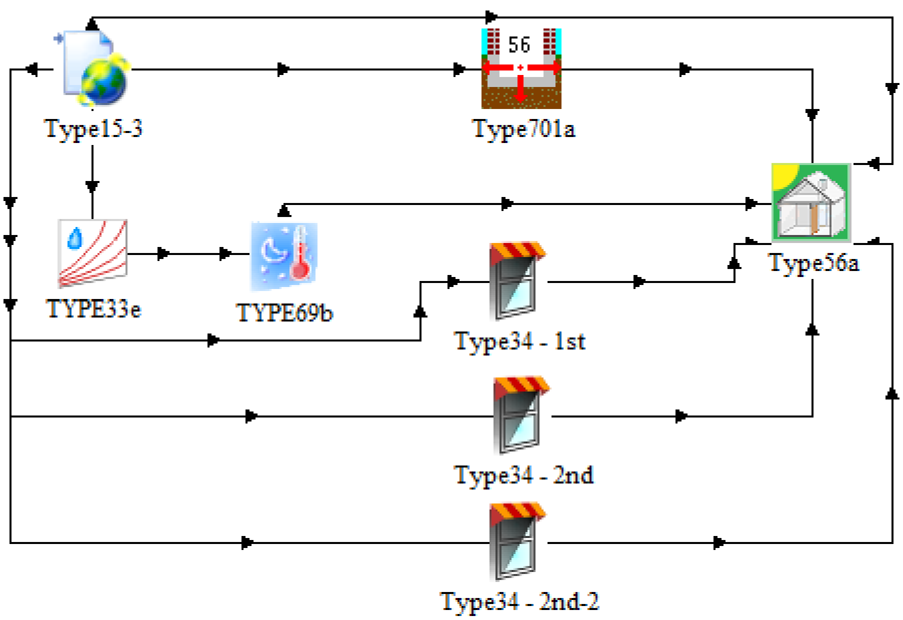

Figure 3.3 – TRNSYS model: weather processing

3.2.2.1. Type 15-3: Weather Data Processor

Type 15-3 combines data reading, radiation processing and sky temperature calculations from an EnergyPlus weather data file. This format is chosen because the weather data for the location of the house, close to the small city of Ste-Agathe-des-Monts, Quebec, was available in this type (U.S. Department of Energy, 2011). While many simulations for Quebec’s climate encountered in technical literature are based on Montreal weather data, it was felt that it would be more accurate to use data from Ste-Agathe-des-Monts, as weather in the Laurentides region differs significantly from the one experienced on Montreal's island. Ste-Agathe-des-Monts is located approximately 80 km north-west of Montreal. Table 3.6 (data from Environment Canada, 2011) draws a comparison between their two climates, which allows to conclude that Ste-Agathe-des-Monts is significantly colder and less windy than Montréal.

Table 3.6 – Comparison of weather data for Montréal and Ste-Agathe-des-Monts

Weather data	Montreal	Ste-Agathe-des-Monts
Degree-days below 18°C	4518.7	5493.2
Total hours of bright sunshine	2028.7	1940.4
Daily maximum temperature in July (°C)	26.2	23.7
Daily maximum temperature in January (°C)	-5.7	-7.8
Average wind speed (km/h)	14.3	10.4

Type 15-3 also calculates incident total, beam and diffuse radiation on each of the building's external surface. Up to 8 surfaces can be defined in the type's parameters by their azimuth and slope. The total radiation, beam radiation and angle of incidence outputs are connected to the corresponding inputs of Type 56, for each defined orientation in the building model. The ground reflectance is set to 0.7 in the presence of a snow cover, which is an input of the weather data, and to 0.2 when there is none.

3.2.2.2. Type 33e: Psychrometrics: Dry Bulb and Relative Humidity Known

Type 33e uses inputs (dry bulb temperature, pressure and relative humidity) from the weather file to call the psychometrics routine in TRNSYS and to return the corresponding moist air properties, such as the dew point temperature (for Type 69) and percent relative humidity (for Type 56).

3.2.2.3. Type 69b: Effective sky temperature for long-wave radiation exchange

Type 69b combines the ambient temperature and dew point temperature coming from type 33e and the beam and diffuse radiation on horizontal surface from type 15-3 to determine the effective sky temperature, which is in turn used to calculate radiation heat exchange between the house, the ground and the sky.

3.2.2.4. Type 701a : Basement Conduction (interfaces with Type56)

Type 701a simulates the complex transient conduction phenomena between the soil, the outside environment and the basement of the house, through a three dimensional finite difference model. The ground is divided into two parts: (1) the near-field, the part of the ground which temperature depends on the heat exchange with the basement and the far-field, and (2) the far-field, where the ground temperature is independent of the near-field. To determine initial temperature at each node, the simulation is first ran for three years, in order to obtain a steady state response. The output file, Happy basecase.soil_out, which contains the nodes' temperature at the end of the year (11:30 P.M. on December 31st), is then used as an input file (Happy basecase.soil_in). Figure 3.4 shows the soil grid for the near-field, as defined by the user (in meters).

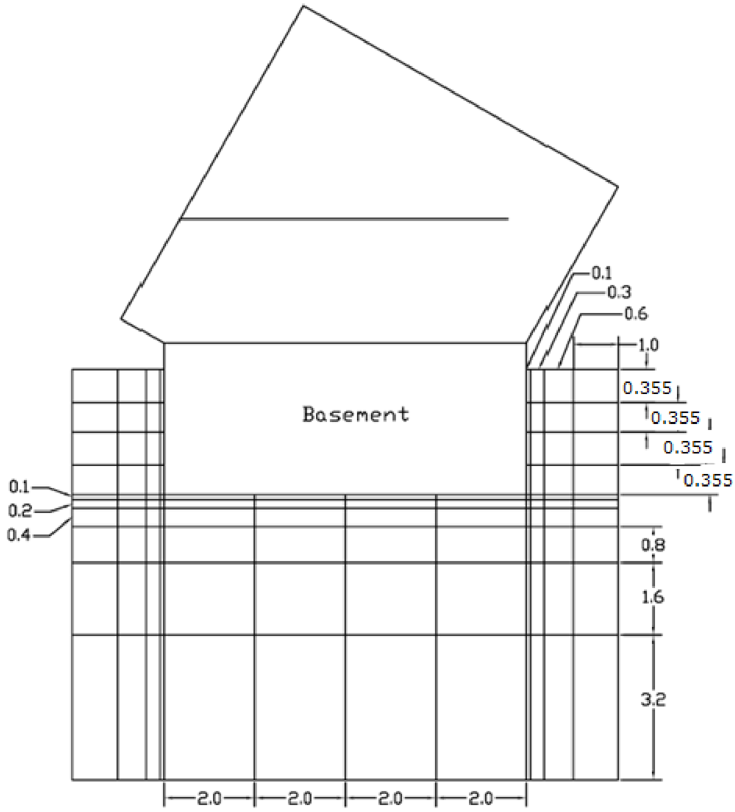

Figure 3.4 – Near-field soil grid geometry (dimensions are in meters)

The model is connected to the fictive sky temperature (Type69b), the ambient temperature (Type15-3), the temperature of walls (Type56b).

3.2.3. Ventilation

Figure 3.5 presents the interconnections between Types for the ventilation portion of the TRNSYS model.

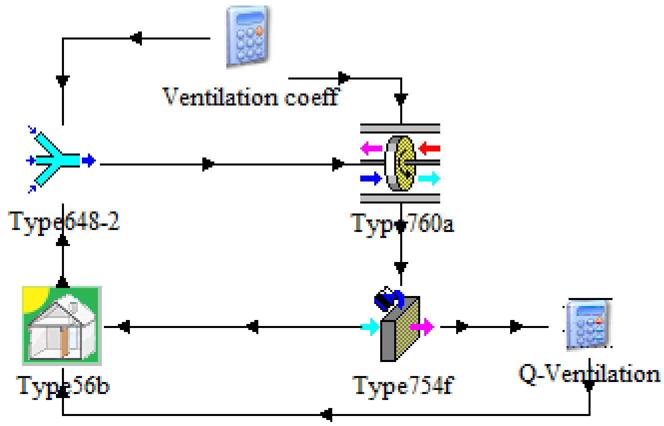

Figure 3.5 – TRNSYS model: ventilation

3.2.3.1. Type 648: Air Mixing Valve with up to 100 inlets

Type 648 takes the temperature, relative humidity and air flow rate coming from each of the two zones (ground-level floor and basement) of the building and combines them to return the properties of inlet air to the heat recovery ventilator.

3.2.3.2. Equation block : Ventilation coefficient

This equation calculates the flow rate for each zone of the building. The required flow rate is obtained from the Québec's *Loi sur le bâtiment* (Gouvernment du Québec, 2000) , which states that each room should be supplied with 5 L/s of fresh air, with the exception of the master bedroom and the basement, which require 10 L/s each. For a 3-bedroom house, this adds up to 50 L/s, or 0.06 kg/s. This flow rate is divided as follow: 20% (10 L/s) for the basement, and 40% (20 L/s) for each first and second floor. The effectiveness of the heat recovery ventilator (HRV) is set to 70%, which is an acceptable value according to the data sheet of a commonly used HRV in Québec (Venmar AVA Solo 2.0). The "season_heaton" value is added to allow bypassing of the heat recovery ventilator while the house does not require any auxiliary heating. Furthermore, natural ventilation is added in the form of increased ventilation flow rate when four conditions are met: it is not heating season, outside temperature is higher than 12°C and more than 2°C lower than the inside temperature, and the second floor air temperature is higher than 24°C. Natural ventilation is equivalent to 6 ACH.

3.2.3.3. Type 515: Heating and Cooling Season Scheduler

Type 515 is a forcing function with two outputs. The first output is season_heaton, which has a value of 1 for every timestep during the heating season, which is defined in a .hcs file as starting on September 1st and ending on June 1st. This is used to turn on the heat recovery function for ventilation as well as the heating system when its value is 1. The second output is cooling_season, which has a value of 1 for every timestep from June 1st to September 1st. It is included in the formula that calculates the cooling temperature setpoint.

3.2.4. HVAC Settings Control

Figure 3.6 presents the interconnections between types for the ventilation portion of the TRNSYS model.

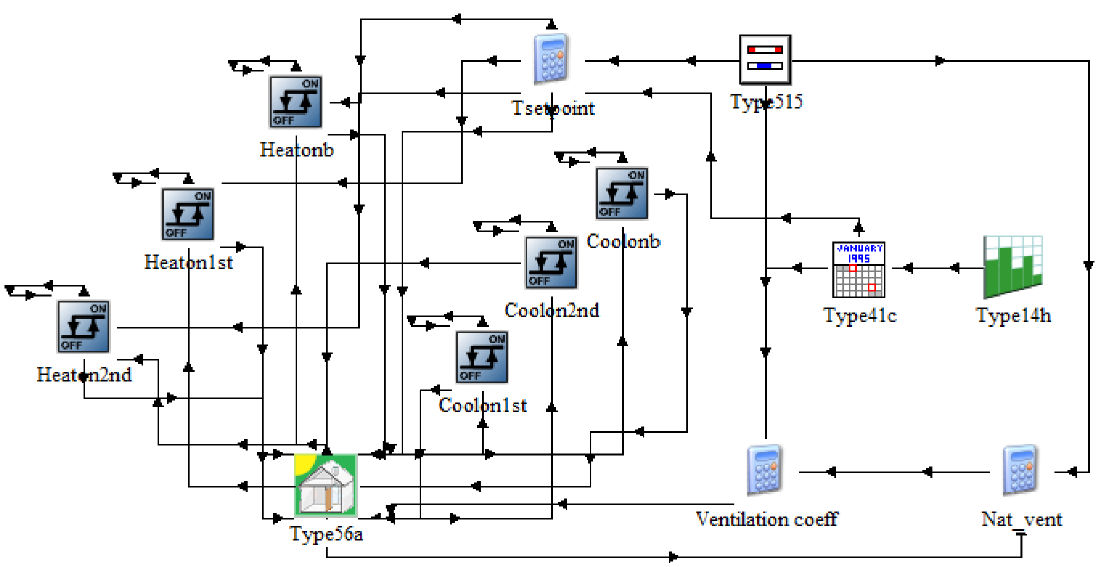

Figure 3.6 – TRNSYS model : HVAC Controls

3.2.4.1. Type 14h: Time Dependant Forcing Function

Type 14h is used to define a function which has a value of 0 at night, and of 1 during daytime (from 6:00 A.M. to 10:00 P.M), to be used to increase the temperature set point during the day.

3.2.4.2. Type 41c : Load Profile Sequencer - Unique Days of the Week

Type 41c takes the daily schedule forcing function defined by type 14h and repeats it to obtain a yearly forcing function, yielding the output *day*.

3.2.4.3. Equation block : Tsetpoint

This equation block uses the output *day* to define the night set-back and day set point. It is to be noted that the heating season indicator is not used here, as it is assumed that occupants will turn on the heat if the temperature is too low, even if it is not heating season. The cooling setpoint is for its part calculated so that it is 24°C during the cooling season, and 34°C for the rest of the year. Since the indoor temperature should always be below 34°C, air conditioning will only be activated during cooling season.

$$T_{setpoint} = (18 + 3 \cdot day) \quad \text{(Eq. 3.7)}$$

$$T_{setpoint\_cool} = 34 - season_{coolon} * 10 \quad \text{(Eq. 3.8)}$$

3.2.4.4. Type 2 : Differential Controllers – Heaton and Coolon

The differential controllers take into account the impact of the thermostat, which has both an upper and lower dead band of 0.5°C. Each zone (basement, first floor and second floor) has its own heating and its own cooling controller. For the heating controller, the output, *heaton*, has a value of 1 when the thermostat detects a temperature that is lower than the set point by at least the value of the lower dead band. This output is connected to the multi-zone building's heating parameter in order to multiply the heating system's power by 0 while the thermostat does not detect a need for heating. The same principle applies to the cooling set point.

3.2.4.5. Type 760a: Sensible Air to Air Heat Recovery with Controlled Outlet Conditions (TESS)

This type uses inputs from the weather data reader (outside air pressure), the psychometrics type (outside air temperature and relative humidity) and the air mixing valve (exhaust air temperature and relative humidity) to model heat transfer between the incoming fresh air and the exhaust air. Efficiency of heat transfer is obtained through the ventilation coefficient equation, which is set to zero during the cooling season, as previously explained at section 3.2.3.

3.3. Simulation results

The heating and cooling loads are investigated for the base case envelope. Figure 3.7 shows the monthly energy profile for the base case envelope.

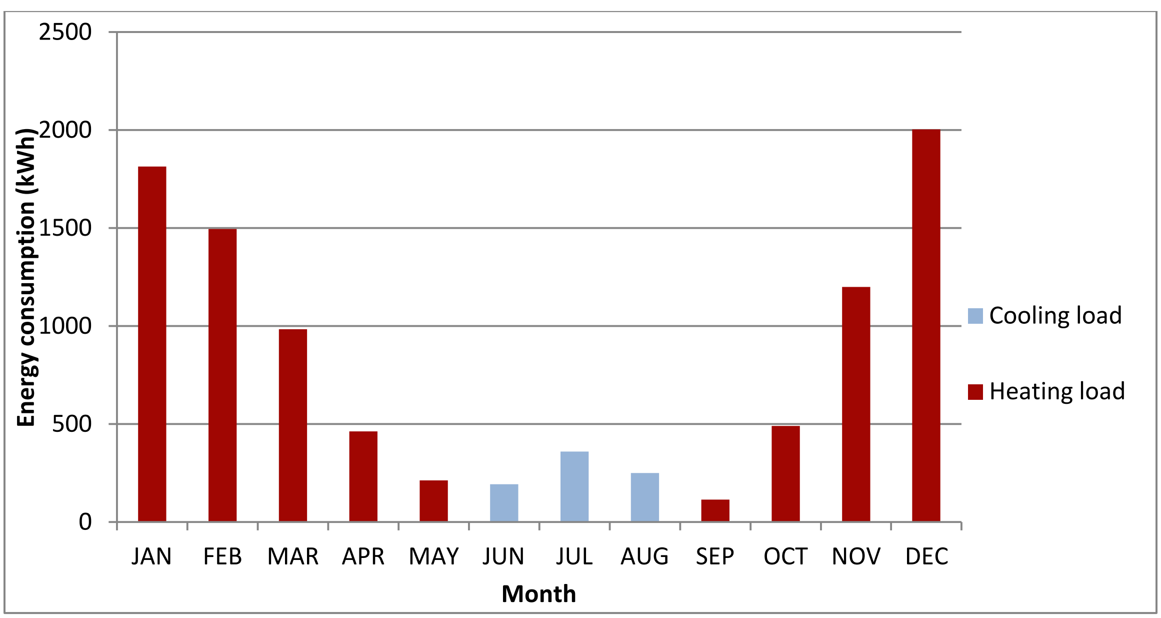

Figure 3.7 – Monthly energy profile of the base case envelope

This figure clearly shows the dominance of heating load (8777 kWh) versus cooling load (804 kWh). With a heating efficiency of 100%, and a cooling COP of 3, this translates into an annual electricity consumption of 9,045 kWh (69.4 kWh/m² of heated floor space), or 8,777 kWh (67.3 kWh/m²) for heating and 268 kWh (2.1 kWh/m²) for cooling.

4. Life cycle optimization of the envelope

In this chapter, the methodology and data for the life cycle cost and energy use optimization of the envelope is explained. Variables considered for the envelope optimization are defined, and the chosen constraints for them are justified. Two objective functions are studied: life cycle cost (LCC) and life cycle energy (LCE).

Then, the data sources for the life cycle energy and cost of materials and components are listed, as well as the assumptions made concerning their lifespan and life cycle phases, amongst others. The structure for the calculation of energy use and cost for each design alternative is outlined.

The third part of this chapter follows with an explanation of the optimization method. This includes the software used, and the optimization algorithm parameters. A methodology to normalize the multi-objective function (for energy use and cost) is presented.

The final section presents the results and analysis of the optimization process.

4.1. Optimization variables

The choice of variables for this optimization considers previous work conducted on envelope optimization in cold climates, which are presented in the literature review chapter of this thesis. Here are some of the most relevant studies. Kassab (2002) defined design alternatives for an energy-efficient house in Montréal, and found the optimal one for different weighted multi-objectives (such as 50% life cycle cost and 50% life cycle energy). However, that study did not compare different insulation materials and includes some parameters that might not be realistic in a real house, such as a heating setpoint of 17°C during the day and 14°C at night. Baouendi et al. (2005) analyzed the life cycle cost, emissions and energy use for five levels of insulation in a typical house using the MNECH assumptions for life cycle analysis (notably, a 30 years study period and a 6% discount rate). Zmeureanu et al. (2005) evaluated life cycle cost, energy use and greenhouse gases emissions for walls with frames ranging from a 38 mm by 90 mm (2 in per 4 in) to 38 mm by 305 mm (2 in per 12 in) wood stud with three different insulation materials. Wang et al. (2005) considered a limited amount of configurations for the wall construction (either steel-framed or masonry cavity walls, with two possible insulation materials each and three thicknesses) in a demonstration of his methodology to minimize LCC versus expended cumulative exergy consumption. Verbeeck and Hens (2007) focused on life cycle cost, life cycle energy and life cycle environmental impacts of residential buildings in Brussels (2933 HDD), while taking into account the thermal resistance of walls for three types of wall construction, but without going into much details about the types of insulation used. Finally, Tuhus-Dubrow and Krarti (2010) optimized only the life cycle cost for dwellings in various climates found in the USA, including the cold climate of Boulder, Colorado (closest ASHRAE weather station, Denver, 3282 HDD). To the best knowledge of the author, no research has been conducted to optimize both life cycle cost and life cycle energy use for dwellings in cold climates while considering various insulation materials and wall constructions. Life cycle energy use is selected as a criterion because of its major impact on environment, namely on resource depletion and eutrophication (Itard, 2007).Variables selected in this study are presented in Table 4.1. All variables are discrete.

Table 4.1 – Optimization variables and their value

#	Variable	Name	Constraints
1	Insulation material – inside of wall	WIns1	Sprayed polyurethane, fibreglass batt, mineral fiber, blown cellulose
2	Insulation material - outside of wall	WIns2	Sprayed polyurethane, extruded polystyrene, foil-faced polyisocyanurate
3	Insulation thickness – inside of wall	WTIns1	[75-250] mm Increment: 25 mm
4	Insulation thickness – outside of wall	WTIns2	[25-100] mm Increment: 25 mm
5	First insulation material for the roof	RIns1	Sprayed polyurethane, foil-faced polyisocyanurate
6	Second insulation material for the roof	RIns2	Fibreglass batt, mineral fiber, blown cellulose
7	Roof insulation thickness	RTIns	[150 – 225] mm Increment: 25 mm
8	Ratio of first insulation material thickness on roof insulation thickness RTIns	RatIns1	[0-1] Increment: 0.20
9	Insulation location and material for the foundation walls	FInsw	Sprayed polyurethane out, extruded polystyrene out, sprayed polyurethane in, blown cellulose in, fibreglass batt in, mineral fiber in, foil-faced polyisocyanurate in
10	Basement walls insulation thickness	FTIns	[75 -175]mm Increment: 25 mm
11	Basement floor insulation material	FInsf	Sprayed polyurethane, extruded polystyrene
12	Basement floor insulation thickness	FTIns_f	[25-100] mm Increment: 25mm
13	Flooring (above ground floors)	Floor	50 mm concrete, 100 mm concrete, hardwood
14	Area of south-facing windows		[10 – 46] m^2 Increment: 4 m^2

The combination of two insulating materials in a wall composition is addressed in the present research, with the objective of representing the actual way walls are built in Canada. Insulation configurations are selected to respect good practices and the

National Building Code for wood studs wall construction, such as the application of exterior insulation that limits thermal bridging and can withstand wet conditions.

Because the choice of an insulation system has an impact on the whole wall system, the envelope is considered as a whole in this optimization. Indeed, as noted by Trusty (2009) about LCA: “comparison may have to be made in a building systems context rather than on a simple product-to-product basis, [which is] more likely to be misleading when dealing with structure and envelope materials, where the system context is the key.” For example, choosing to insulate the basement foundation from the outside results in the need to add a finish system (such as vinyl cladding) above ground, in order to protect the insulation from the sun rays. Furthermore, the impact of different wall and roof framing systems is assessed in this study, to consider the additional embodied energy inherent to bigger frames when large amounts of insulation are used. The framing system is not an independent variable, as it is chosen with respect to the space needed for the insulation thickness selected. The framing system also has an impact on the effective thermal resistance of the wall because of the thermal bridging effect, as explained in Chapter 3.

The insulation thickness range of values is selected to allow the thermal resistance of walls and roof to vary between the minimal requirements as defined by the Réglement sur l’économie d’énergie dans les nouveaux bâtiments (Gouvernement du Québec, 1992), and very high insulation levels as set by other advanced green building projects that were studied in the literature review. The maximum thicknesses are also dictated by the framing systems, which were chosen amongst the most common systems in green buildings, while taking in consideration the manufacturer’s capabilities. For example, because the model house has a flat roof and has to be transported into modules to the construction site, the roof frame could only have a maximum thickness of about 225 mm, therefore limiting the structure to wood studs no wider than 191 mm (8’’ nominal dimensions). Walls thickness is not as limited by transportation criteria; however, the outside dimensions of the house are fixed and consequently, any additional thickness reduces the available living space, and therefore has a cost penalty associated to it. How this is addressed in the life cycle cost calculation is explained in section 4.2.2.

The list of insulation materials is chosen based on several of the following criteria: availability, value, embodied energy, thermal resistance and common use in green building projects. Table 3.2 summarizes the characteristics of some common insulation materials per area of 1 m^2 and thickness of 25.4 mm (which is the standard available thickness on the North American market for panels and batts). Sprayed polyurethane has one of the highest thermal resistances per unit of thickness, and it was used in most of the green buildings studied in the literature review. Polyisocyanurate foil-faced rigid boards are interesting for their outstanding thermal resistance, which reaches a value of up to 1.17 $m^2 \cdot K/W$ per 25.4 mm (CHMC, 2009a). It also has the advantage of having an embodied energy that is half the one of sprayed polyurethane, but more GHG are emitted for its production (Athena Sustainable Materials Institute, 2008). Cellulose is selected for its extremely low embodied energy, due to the fact that it is made entirely from recycled paper. Extruded polystyrene has a rather high thermal resistance, and is widely used for outside stud insulation, as well as for insulation outside foundation because of its resistance to moisture. Fibreglass batt is interesting for its low cost, and has lower embodied energy than mineral fiber. However, mineral fibre has a better thermal resistance.

Some other criteria are not formally assessed because of a lack of numerical values, but are nevertheless worth mentioning. Polyurethane and cellulose both improve air tightness of the envelope thanks to their ability to fill in small cavities. However, polyurethane also has the bad quality of acting as a combustible in case of fire.

Accordingly, sprayed polyurethane and extruded polystyrene are considered for outside and foundation insulation, while sprayed polyurethane, cellulose, fibreglass, mineral and polyisocyanurate are used inside of walls and roof.

Table 4.2 – Properties of some insulating materials

Material	Cost for material and installation ($\$/m^2/25.4$ mm)[1]	Thermal resistance ($m^2 \cdot K/W$ for 25.4 mm)[2]	Embodied energy ($MJ/0.0254\ m^3$)[3]
Blown cellulose	3.53	0.65	1.5
Extruded polystyrene	12.52	0.88	74.1
Fiberglass batt	4.45	0.59	13.9
Foiled-faced polyisocyanurate	10.95	1.34	62.0
Mineral fiber	5.59	0.71	27.4
Sprayed polyurethane	18.39	1.00[4]	112.9[5]

[1] RS Means (2010) and in-house estimation data
[2] Unless otherwise noted, ASHRAE (2009)
[3] Unless otherwise noted, Athena Sustainable Materials Institute (2008)
[4] Demilec Canada (2009)
[5] Petersdorff et al. (2002)

Another important optimization variable that is not considered in this work is the window type. Indeed, it has been concluded in various previous researches that triple-glazed windows are superior to double-glazing. Hasan et al. (2008) concluded that windows with a U-value of 1.0 $W/m^2.K$ (equivalent to triple-glazed low-e windows) instead of 1.4 $W/m^2 \cdot K$ (equivalent to double-glazed low-e windows) led to a reduced life cycle cost in Helsinki (4856 HDD), which is a cold climate that could be compared to the one in Québec. In their extensive life cycle cost, energy and GHG emission optimization, Verbeeck and Hens (2007) suggested that windows with a U-value of 1.1 $W/m^2 \cdot K$ was one of the most cost-effective economical way to achieve a low-energy building in Brussels, Belgium (2933 HDD). Moreover, EQuilibrium projects from Québec and Ontario that were previously discussed have selected triple-glazed low-e windows. However, it is to be noted that those projects were not based on life-cycle optimization, but rather on minimizing annual energy consumption.

Finally, because their greater thickness makes them inconvenient for handling and design considerations, the developer prefers to avoid using quadruple-glazed windows, which made any optimization of the glazing system unnecessary for this work. Accordingly, all windows are assumed to be triple glazed with double low-e and fibreglass framing. To preserve the architectural look of the building, size and position of windows are not modified throughout the optimization process.

4.2. Data and assumptions for life cycle calculations

As life cycle analysis (LCA) can rely on various assumptions and encompass variable life phases of a product, it is of great importance to define the scope of the analysis that is performed as part of the optimization procedure in this thesis. First of all, some house components are not considered for the envelope optimization because they are too specific to the house owner and to the particular site chosen for construction. With this in mind, all excavation and site work are not taken into account. Of course, mechanical systems are not considered for this part of this optimization as they will be the subject of the following chapters.

The life cycle period is set to 50 years for two reasons. First, most of the life cycle analysis or optimizations conducted on single-unit residential buildings found in the literature use this time frame. In a review article on the life cycle energy use of conventional and low-energy buildings by Sartori and Hestnes (2006), 6 out of the 9 quoted life cycle analysis of single-unit residential buildings use a life cycle time frame of 50 years. Other studies are based on 30 years, 80 years or annualized values. On the other hand, the Model National Energy Code of Canada for Houses

(CCBFC, 1997) uses a time frame of 30 years that corresponds to the economic life of the building (ie. the period for which the building will be used without needing major renovations). However, this document also notes that “it can be argued that [the numbers of year considered] should be the life of the building, which might exceeds 100 years”. Indeed, the choice made for the design of the envelope will have an impact on a longer period than the time for which the buyer plans on occupying the house. A period of 50 years then allows giving proper value to the environmental impacts of the building while still being short enough to make reasonable assumptions on the repairs and maintenance to be made.

4.2.1. Life cycle primary energy use (LCE)

For the purpose of the life cycle energy optimization, all life cycle inventory data is collected in terms of primary energy. Even though one should include all life phases in a LCA, from cradle to grave, this heavily depends on the availability of life cycle inventory data. Indeed, it is beyond the scope of this thesis to conduct research on life cycle primary energy of individual materials. Furthermore, data extracted from a specific life cycle inventory database is expected to be more consistent, as a defined methodology is used for all materials. Most of the materials primary energy use data used in this work comes from the ATHENA Impact Estimator. According to the Athena Sustainable Materials Institute, the non-profit organization that has developed the Impact Estimator, it is “the only software tool that is designed to evaluate whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology” (Athena Sustainable Materials Institute, N/A).

Accordingly, life phases chosen for this analysis are the same as the ones available in the ATHENA Impact Estimator (with the addition of operation energy, as calculated by TRNSYS): manufacturing, construction, maintenance and end-of-life. However, some materials could not be found in this database. The author then relied on scientific literature to fill in the gaps, while making sure that all articles presented primary energy use. Data extracted from the literature (other than from the ATHENA Impact Estimator) was limited to manufacturing primary energy use, therefore excluding construction, maintenance and end-of-life phases. While this induces an error, it was decided not to try to estimate primary energy use for those phases, as they represent only a small fraction of the life cycle energy. For example, in the case of polyisocyanurate insulation, construction, maintenance and end-of-life represent only 0.5 MJ of primary energy, compared to 61.5 MJ for manufacturing (Athena Sustainable Materials Institute, 2008). However, construction primary energy use is not negligible for walls and roof assemblies; those are all evaluated with the ATHENA Impact Estimator to take this phase into account. It is also to be noted that articles used to obtain values of embodied energy for materials not covered by ATHENA were specific to certain geographic areas. For example, Alcorn (2003) studied embodied energy in construction materials in New Zealand, and Petersdorff et al. (2002) gave energy data pertaining to insulation materials for continental Europe. This is another source of error, but is considered as an acceptable estimate in the absence of better data. Materials and primary energy data as modeled for the modular house is listed in Appendix B.

All primary energy use data includes waste factors and replacement when the material lifespan is shorter than the house lifespan of 50 years. A bill of material including quantities for all envelope design alternatives, as well as waste factors (taken from ATHENA Impact Estimator) and lifespan are available in Appendix B.

The envelope life cycle primary energy use for the selected design alternative is then calculated using equation 4.1:

$$LCE = \sum_i LCE_{assembly_i} + 50 \cdot Energy_{op} \qquad \text{(Eq. 4.1)}$$

where $LCE_{assembly}$ is the embodied energy in each of the assemblies (roof, exterior walls, floors, etc.), including the manufacturing, construction, maintenance and end-of-life phases, and $Energy_{op}$ is the primary electrical energy used for heating and cooling the house for one year, as shown in equation 4.2.

$$Energy_{op} = F_{primary}\left(load_{heating} + \frac{load_{cooling}}{COP_{cooling}}\right) \qquad \text{(Eq. 4.2)}$$

$COP_{cooling}$ is assumed to have a value of 3 and the load for heating is equal to the electrical energy consumed, meaning that heating is provided by electrical baseboards with an efficiency of 100%. $F_{primary}$ is the conversion factor applied to transform site-used electrical energy into primary energy, including production and distribution losses. This factor is calculated using Quebec electricity mix taken from 2007 data (Statistics Canada, 2009), which is: 94.4% hydraulic, 2.2% natural gas, 2.1% nuclear, 0.6% heavy fuel, 0.3% wood and others and 0.1% light fuel and diesel. Those numbers include Québec imports from Labrador and Newfoundland (which represent about 15.9% of the 191,734,530 MWh used in the province that year), but excludes imports from the US (3,355,838 MWh) because of a lack of data on imported electricity mix. Efficiencies used in calculations for each type of electricity generation are listed in Table 4.3.

Table 4.3 – Efficiencies of electricity generation technologies

Electricity generation technology	Efficiency	Source	Notes
Hydraulic	85%	Østfold Research Foundation (2002) and Ílerí A. and Gürer T. (1998)	First reference give efficiency for a recent hydraulic power plant in Norway in 2007 (90%), while the second is for Turkey in 1995 (80%)
Natural gas	43%	Graus et al. (2007)	United States data
Nuclear	30%	Rosen M.A. (2001)	Canada data
Oil fired	36%	Graus et al. (2007)	United States data
Wood and others	30%	-	Wood and others mix is difficult to quantify, so the lowest efficiency is assumed

The average primary energy conversion efficiency obtained from the calculated electricity mix and assumptions on generation efficiencies is 82.2%. To that amount, one needs to add the distribution losses, which are assumed to be 6% from Québec (Lafrance, 2006, as quoted by Zmeureanu and Wu, 2007). In order to obtain the primary energy consumed, the secondary energy value is multiplied by conversion factor $F_{primary}$ is then the inverse of the total production and distribution efficiency, which gives 1.29.

Table 4.4 gives the LCE of the base case house, as an example of the contribution of the embodied energy in assemblies versus the operation energy. Maintenance energy is included into the assembly's embodied energy, as presented in the ATHENA Impact Estimator.

Table 4.4 – LCE for the base case house

Assembly	Primary energy use (MJ)	Percentage of total LCE
Total embodied energy	**469,964**	**17.9%**
Roof	157,913	6.0%
Exterior walls	109,855	4.2%
Partition walls	9,441	0.4%
Floors	27,336	1.0%
Foundation	94,955	3.6%
Windows and doors	49,507	1.9%
Outside frame of modules	20,957	0.8%
Total primary operating energy use	**2,158,307**	**82.1%**
Yearly operating primary energy	43,166 (9,257 kWh)	-
TOTAL LIFE CYCLE ENERGY	**2,628,001**	**100%**

It can be observed that embodied energy represents a rather significant portion (18%) of the total LCE of the base case building. While this is a high figure, it has been observed in the past that embodied energy of low-energy houses can represent as much as 60% of the total LCE (Gustavsson and Joelsson, 2010). This can be partially attributed to the use of polyurethane for insulation, which accounts for about 18 percents of the embodied energy. For comparison purposes, 25 mm of polyurethane used to insulate the outside of the exterior walls adds 21,005 MJ to the embodied energy of the house, while 138 mm of cellulose put inside the exterior wall cavities represents only 1,559 MJ. Another very energy intensive material is the commercial steel roofing that is used: that component makes up for 22 percents of the envelope's embodied energy. For a detailed table of components' embodied energy, refer to Appendix B.

4.2.2. Life cycle cost (LCC)

The life cycle cost criterion is based on the selling cost to the final occupant. Most of the cost data per unit of material comes from the RS Means Residential Cost Data 2011 book (RS Means, 2010). Prices from this database are corrected for St-Jérôme (small town north of Montreal, close to the actual building location) using the location factor given in the book, which is 1.15. It also includes the currency exchange rate, from US dollar to Canadian dollar. Prices obtained from RS Means Residential Cost Data 2011 include 20 percent overhead and profits. A sales tax of 13.925% (composed of a federal tax of 5%, and a provincial tax of 8.5%) is also added to all prices, as applicable. The same material quantity, waste factors and lifespan as those specified for the life cycle energy calculations apply.

A penalty cost is added for exterior wall systems that take up more space than the minimum 38 mm per 140 mm (2 in per 6 in) wood stud framing walls and 25 mm of exterior insulation. As modules have given exterior dimensions, any wall that is thicker takes up some of the living space. For each square meter of floor area lost to insulation and framing, there is an additional cost of $970 which corresponds to the selling cost per square meter of floor area that the developer is aiming at.

All prices are given in 2011 constant dollars. Since constant dollars are used, a real discount rate and a real escalation rate are used to calculate the present value of each cost, in order to combine them into a meaningful life cycle cost. The real discount rate represents the time-value of money, excluding inflation, while the real escalation rate is the increase or decrease (if negative) of the price of a good, excluding inflation (Fuller and Petersen, 1996). The real discount rate used is calculated based on a nominal discount rate equal to the average interest rate for the period between 2001 and 2011 (Bank of Canada, 2011b), and an inflation rate also equal to the average for Canada during this period (Bank of Canada, 2011a). Equation 4.3 defines the real discount rate *d*:

$$d = \frac{1 + D}{1 + I} - 1 \qquad \text{(Eq. 4.3)}$$

where the nominal discount rate D is 0.0269 (2.69%) and the inflation rate I is 0.0203 (2.03%), for a real discount rate of 0.0065.

Life cycle costs considered for the envelope are part of three main categories: investment costs, maintenance and replacement costs, and operation costs. Municipal taxes, insurance and other similar costs are not considered. The investment cost C_{invest} is the cost of the initial envelope, which occurs at the beginning of year 1, and is consequently already in constant dollars. Maintenance and replacement costs, $C_{M\&R}$, include repainting of interior walls (every 8 years), replacement of vinyl siding (every 35 years), replacement of windows (every 25 years), replacement of fiber-cement siding (every 30 years) and repainting of fiber-cement every 15 years. Replacement costs are assumed to have the same cost in constant dollars, and are discounted from the end of the year at which they occur, following equation 4.4 to calculate the present value of an amount occurring a single time (Fuller and Petersen, 1996). Operation costs are the annual costs of electricity for heating and cooling C_{energy}; they are discounted at the end of each year. Electrical energy is assumed to have a real escalation rate of 2%. This value is subject to debate; the MNECH 1997 assumes a real escalation of 0% for the province of Quebec in its LCC calculation. However, in other studies, scenarios where the annual escalation rate for electricity varies from -1% to 5% are considered (Peippo et al. 1999, Keoleian et al. 2001, Hasan et al. 2008, Palonen et al. 2009). Some might argue that electricity prices in Quebec have been closely following inflation in the past decade (Leckner, 2011), but the author thinks that in a context where the electricity demand continues to rise and new hydro-electricity projects are more and more expensive due to the lack of new rivers that can easily be harnessed, it is too optimistic to think that energy prices will stay at their extremely low levels in Quebec. To take into account the effect of both escalation and discount rates of the 2011 constant dollar price of energy, equation 4.5 is used, which applies to obtain the present value $PV_{recurring}$ of an amount that has to be paid annually (Fuller and Petersen, 1996).

$$PV_{single} = \frac{F_t}{(1+d)^t} \tag{Eq. 4.4}$$

$$PV_{recurring} = A_o \frac{(1+e)}{(d-e)}\left[1-\left(\frac{1+e}{1+d}\right)^n\right] \tag{Eq. 4.5}$$

where F_t is the cost at the year of occurrence t (with respect to the year of reference for present value), A_o is the cost of electricity for the first year of operation, e is the real escalation rate for electricity and n is the period over which energy costs occur, in years. The life cycle cost for each design alternative LCC_{env} is then calculated using equation 4.6:

$$LCC_{env} = C_{investment} + C_{M\&R} + C_{energy} \tag{Eq. 4.6}$$

where $C_{investiment}$ is not discounted, $C_{M\&R}$ is the sum of each maintenance and replacement, discounted at its year of occurrence using equation 4.4, and C_{energy} is calculated using the cost of electricity for year 1 in equation 4.5. For 2010, the average cost of electricity for residential customers for a monthly consumption of 1000 kWh in the province of Québec was 6.88$/kWh (Hydro-Québec, 2010), to which are added taxes (13.925%), for a total of 7.84$/kWh. That price is used for year one of the life of the building.

Table 4.5 gives the LCC of the base case house, divided into assemblies and operation costs, as an example of the contribution of the house cost versus the operation cost.

Table 4.5 – Life cycle cost for the base case house

Assembly	Life cycle cost (constant 2011 CAD)	Percentage of LCC
Total material cost	**273,321**	**84.0%**
Roof	23,121	7.1%
Exterior walls	53,247	16.4%
Partition walls	5,293	1.6%
Floors	26,615	8.2%
Foundation	30,860	9.5%
Windows and doors	100,008	30.7%
Outside frame of modules	34,178	10.5%
Total energy cost for 50 years	**51,920**	**16.0%**
Yearly energy cost (first year)	725.75	0.2%
TOTAL LIFE CYCLE COST	**325,240**	**100%**

4.3. Optimization procedure

GenOpt 3.0.3 (Lawrence Berkeley National Laboratory, 2010) is a program that optimizes one given objective function calculated by a building simulation software, using an optimization algorithm selected by the user from a bank of available algorithms. The building simulation software must read text input and write text output in order to be compatible with GenOpt. This program is particularly useful to optimize building operation cost or energy because it can deal with discontinuous functions or functions for which analytical properties (such as the gradient) are not available.

4.3.1. Interaction between GenOpt and TRNSYS

Figure 4.1 presents the general steps executed by both GenOpt and TRNSYS for an iteration of the optimization algorithm.

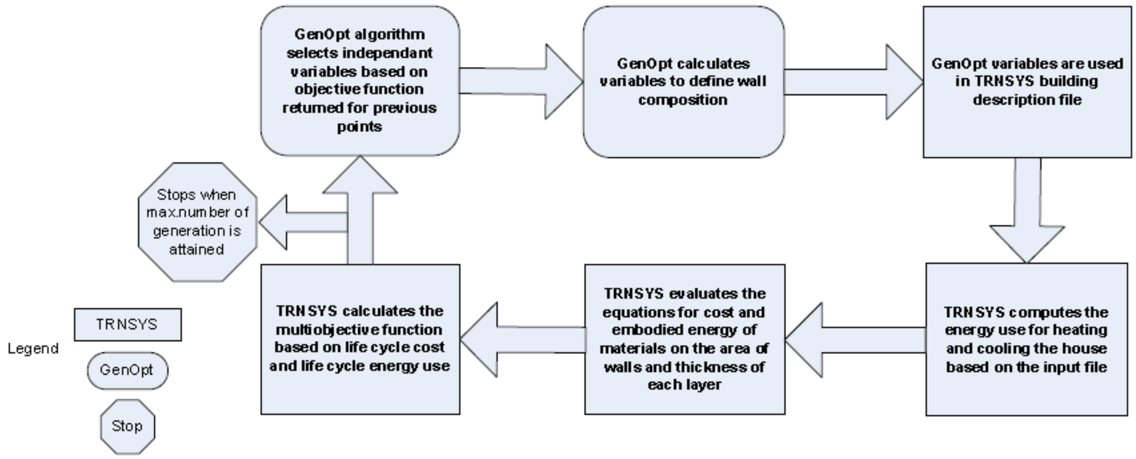

Figure 4.1 – Flowchart of interaction between TRNSYS and GenOpt

For each iteration of the optimization algorithm, GenOpt sets the value of all the independent variables as outlined in Table 4.1. It also calculates the value of intermediate variables through functions programmed in the GenOpt initiation file. Intermediate variables are the thickness for each layer, which can in turn be used by TRNSYS to define each wall composition. It is to be noted that for TRNSYS, a wall type is defined as any surface separating inside zones from each other or the outside environment. Consequently, the roof and the inside floors are also named “walls”. Tables 4.6 and 4.7 give an example of how the variables are handled by both GenOpt and TRNSYS for the roof wall.

Table 4.6 – Genopt independant variables for the roof

Variable	Value (Increment)	Meaning
RTIns	[150-225] (25)	Total thickness of insulation for the roof, in mm
RatIns1	[0-1] (0.25)	Ratio of the insulation that is occupied by insulation material 1 (RIns1)
RIns1	0	Sprayed polyurethane is the material occupying the first portion of the roof insulation
	1	Foil-faced polyisocyanurate is the material occupying the first portion of the roof insulation
RIns2	0	Fiberglass batt is the material occupying the second portion of the roof insulation
	1	Blown cellulose is the material occupying the second portion of the roof insulation

Table 4.7 – TRNSYS roof model variables (from the inside to the outside)

Layer	Variable name	Equation for thickness (in m)
Gypsum board	-	0.013
Air layer	-	0.015
Fiberglass batt	RTFiber	If *RIns2*=1: *RTIns* x (1 - *RatIns1*) + 0.001 If *RIns2*=1: 0.001 If RIns2=3: 0.001
Blown cellulose	RTCellu	If *RIns2*=1: 0.001 If *RIns2*=2: *RTIns* x (1 - *RatIns1*) + 0.001 If RIns2=3: 0.001
Mineral wool	RTMineral	If *RIns2*=1: 0.001 If RIns2=2: 0.001 If *RIns2*=3: *RTIns* x (1 - *RatIns1*) + 0.001
Sprayed polyurethane	RTPolyu	If *RIns1*=0: *RTIns* x *RatIns1* + 0.001 If *RIns1*=1: 0.001
Foil-faced polyisocyanurate	RTPolyi	If *RIns1*=0: 0.001 If *RIns1*=1: RTIns x RatIns1 + 0.001
Plywood	-	0.019
Steel roofing	-	0.001

One mm is added to each of the layer's thickness because a nil thickness value would make the transfer function for heat transfer impossible to be calculated numerically. Because it is not possible to use logic functions (such as "if") in the Fortran library used in GenOpt, 1 mm is also added if the layer's thickness is not nil. Table 4.8 shows the series of equations that transform the parameters RIns2, RatIns1 and RTIns into a layer thickness for each of the material. The example of the cellulose layer for the roof insulation is displayed. This example is valid for all insulation layers, the only difference being that the first operation would be RIns2-1 if the thickness for fibreglass was to be calculated, or RIns2-3 if it was for mineral wool.

Table 4.8 – Series of operations to calculate insulation layer thickness

Item	Operation	Notes
1	Op1 = RIns2-2	If RIns2=2, equals 0.
2	Op2 = abs(Op1)	If RIns=2, equals 0. Otherwise, equals >0.
3	Op3 = min(Op2, 1)	If RIns=2, equals 0. Otherwise, equals 1.
4	Op4 = 1-Op3	If RIns2=2, equals 1. Otherwise, equals 0.
5	Op5 = RTIns2 * Op4	If RIns2=2, equals RTIns2. Otherwise, equals 0.
6	RTCellu = Op5+0.001	Layer thickness as used in TRNBuild, with an excess of 1 mm to avoid nil values.

Some test runs were conducted to validate the impact of using layers of 1 mm thickness. The impact on the energy loads for the base case house, which has a rather low insulation level and therefore is highly affected by additional thin layers of insulation, is that the heating load drops by 5.0%, while the cooling load increases by 6.3%, for a total impact on the heating and cooling load of +3.9%. In the case of a design alternative with maximum insulation, the relative impact would of course be smaller. However, considering other sources of uncertainties involved in computer modeling of buildings energy consumption, an error of that magnitude is judged as acceptable.

TRNSYS then calculates the operating energy for that house envelope case (as detailed in chapter two), as well as the embodied energy for each of the assemblies. Embodied energy data is included in TRNSYS in the form of equation blocks, where the variables are linked to the values defined in GenOpt. The equations are built with Fortran language operators. As an example, equation 4.7 is used to calculate the embodied energy contained in the roof frame and insulating materials. Embodied energy for materials that are not modified through optimization (steel roofing, gypsum, etc.) are calculated in a separate equation.

$$LCE_{Roof} = LCE_{2x6R} + gt(RTIns, 0.175) \cdot LCE_{IncR_{2x8}} + 64 \cdot (RTPolyu \cdot 4667 + RTPolyi \cdot 2440 + RTFiber \cdot 546 + RTCellu \cdot 58) \qquad \text{(Eq. 4.7)}$$

where LCE_{2x6R} is the LCE for the materials in the 38 mm per 140 mm (2” per 6” nominal) wood stud frame (in MJ), *gt* is a Boolean operator that returns 1 if *RTIns* is greater than 0.175, and 0 if it is not the case, and $LCE_{IncR2x8}$ is the increment in LCE (in MJ) if changing the 38 mm per 140 mm frame for a 38 mm per 191 mm (2” per 8” nominal) wood stud frame. The numbers between the brackets (4667, 2440, 546 and 58) are the LCE value in MJ per m^3 for each of the insulating material. A similar equation is written for each of the assembly (ie. walls, floors, basement walls and floor).

4.3.2. Algorithm parameters

GenOpt can be set up to use one of many available optimization algorithms, amongst the followings: Coordinate Search, Hooke-Jeeves, Particle Swarm and Hybrid General Pattern Search with Particle Swarm. GenOpt does not support multi-objective optimization, hence only one cost function can be selected. Also, no Genetic Algorithm is included in its algorithm bank; to be used in GenOpt, this type of algorithm would have to be coded by the user, which is beyond the scope of this thesis. Accordingly, it is chosen not to use a genetic algorithm and to combine both objectives (LCE and LCC) into one objective function. The development of the objective function is explained in the following section.

The GenOpt manual (Wetter, 2009) gives detailed instructions on which algorithm is best suited to each type of optimization problem. In this case, all variables are discrete, in an effort to obtain realistic values; for example, insulation in the walls can only be added by increments of 25 mm, as most materials on the North American market are available in this format. The suitable algorithm in those available from GenOpt, for the case where only discrete variables are used, is the Particle Swarm Algorithm. This algorithm has a version where variables are encoded and treated as a string of binary numbers, which makes the use of discrete variables possible.

The Particle Swarm algorithm is a population-based probabilistic optimization algorithm. It was first proposed by Kennedy and Eberhart in 1995, and mimics the movement of a flock of birds or a school of fish (Wetter, 2009). Each individual of a population is called a particle, and represents a point in the search space which is a potential solution. For each generation (or iteration of the algorithm), a population of particles is defined, and each particle's position changes depending on where it had its lowest cost function value (cognitive behaviour), as well as on where other particles had their lowest cost function value (social behaviour), in order to reach the global minima of the cost function. The basic mathematical implementation of this algorithm is explained below.

The position of the particle in the D-dimensional search space is defined by a D-dimensional vector x. For each particle of each iteration, a velocity vector v is calculated as the sum of three terms: (1) the previous velocity vector, (2) the difference between the particle's best position yet p_i, and its current position x_i, multiplied by the cognitive acceleration constant c_1 and a random number r_1, and (3) the difference between the position of the swarm's best particle p_g and the particle's current position x_i, multiplied by the social acceleration constant c_2 and a random number r_2. While v is named a velocity vector in the PSO algorithm theory, it is actually a displacement vector, so that it can be added to the particle's position vector. The new position of the particle is then the sum of its previous position and the velocity vector. This process can be summarized by equations 4.8 and 4.9 (Parsopoulos and Vrahatis, 2002).

$$v_{id}{}^{n+1} = v_{id}{}^{n} + c_1 r_1{}^{n}(p_{id}{}^{n} - x_{id}{}^{n}) + c_2 r_2{}^{n}(p_{gd}{}^{n} - x_{id}{}^{n}) \quad \text{(Eq. 4.8)}$$

$$x_{id}{}^{n+1} = x_{id}{}^{n} + v_{id}{}^{n+1} \quad \text{(Eq. 4.9)}$$

where n is the number of the generation.

Many parameters for this algorithm can be modified in GenOpt. First of all, two main variations of the Particle Swarm Optimization Algorithm are available: with inertia weight or constriction coefficient. Because constriction coefficient has a tendency to get stuck in local minima (Kennedy and Eberhart, 2001), the inertia weight is chosen, even if it usually is slower to converge. Then, three topologies are available: lbest, gbest and Von Neumann. A topology is the way each particle makes connections with its neighbours, that is, which other particles affect its evolution. Gbest topologies connect each particle with all the other particles. While gbest lets the particle be influenced by all of the other particles, the lbest and Von Neumann topologies limit that influence to a neighbourhood. In lbest topologies, each particle only has one neighbour on each side, forming a closed circle. The Von Neumann topologies can be represented by a bi-dimensional grid, where each particle has four neighbours, corresponding to the four cardinal directions. Kennedy and Mendes (2002) found, when comparing the results on standard test functions of six typologies including those three, that the Von Neumann typology did consistently quite well with most performance indicators, which is why it is selected for this optimization.

Researchers make different recommendations when it comes to selecting a population size and a maximum number of generations. As summarized by Wetter (2009): Parsapoulos and Vrahatis (2002) suggest using a population size of five times the number of independent variables (equal to 70 in this case) with 1000 generations, Van den Bergh and Engelbrecht (2001) suggest a population size greater than 20 with 2000 to 5000 generations, while Kennedy and Eberhart (2001) say that a population size between 10 and 50 usually works well. Because such a large number of generations is unpractical with a computation time of over 2 minutes per particle, a population size of 30 with a maximum of 80 generations is chosen in this study by trial and error.

Cognitive acceleration constant c_1 is given a value of 2.5, and 1.5 is chosen for social acceleration constant c_2, following the conclusions of Carlisle and Dozier (2001). MaxVelocityGainContinuous is set to 0 in order to not use velocity clamping, and MaxVelocityDiscrete is equal to 4, to avoid saturation of the sigmoid function, according to Wetter (2009).

4.3.3. Combination of the objective functions

One approach that is often used for multi-objective optimization, other than finding the Pareto front with a Genetic Algorithm, is to merge the all of objective functions into one global objective functions by using weighted factors (Hauglustaine and Azar Lema, 2001, Kassab, 2002, Alanne et al., 2007). However, it is of importance to choose correct weighting factors depending on the order of magnitudes of each criterion's objective function.

Alanne et al. (2007) apply this concept in a multi-criteria evaluation of residential energy supply systems. To obtain comparable values of all five objectives (life cycle cost, use of abiotic resource, use of water, global warming potential and acidification potential, which all have different units), all values are normalized within a range of 0 to 1. Weighting factors, which add up to 1, then have a significant meaning: if two objectives are assigned a weighting factor of 0.5 each, they indeed are worth half of the total normalized cost function.

To implement this methodology, life cycle cost was first minimized and the corresponding life cycle energy use was obtained, and then life cycle energy use was minimized and the corresponding life cycle cost obtained. This is equivalent to a multi-objective optimization that use weighting functions with weighting coefficients of 0 and 1. The minimal and maximal value for LCE and LCC are then used to normalize the objective function *F* for each design alternative, as stated in equation 4.10. In each case, the sum of w_1 and w_2 is 1.

$$F = w_1 \frac{LCC_{env} - LCC_{min}}{LCC_{max} - LCC_{min}} + w_2 \frac{LCE_{env} - LCE_{min}}{LCE_{max} - LCE_{min}} \quad \text{(Eq. 4.10)}$$

The value of objective function *F* returned by each particle is used by GenOpt to choose particles to be evaluated in the next generation, until no better particle can be found or the number of generation has attained the specified limit.

4.4. Results

Table 4.9 presents the objective function values (life cycle cost and life cycle energy) as well as the properties of the optimal envelope found by the PSO algorithm for three different values of weighting factor *w1* (as used in equation 4.10).

Table 4.9 – Comparison of the minimum LCC and LCE design alternatives

	w1 = 1 (minimum LCC)	*w1 = 0 (minimum LCE)*	*w1 = 0.5*
Life cycle cost	$246,149	$254,290	$247,787
Life cycle energy	1,910,210 MJ	1,495,201 MJ	1,641,345MJ
First roof insulation layer	None	135 mm polyisocyanurate	90 mm polyisocyanurate
Second roof insulation layer	225 mm fibreglass batts	90 mm blown cellulose	135 mm fibreglass batts
Roof effective thermal resistance	5.44 $m^2 \cdot K/W$	7.51 $m^2 \cdot K/W$	6.91$m^2 \cdot K/W$
Wall cavity insulation	75 mm fibreglass batts	250 mm blown cellulose	175 mm fibreglass batts
Wall insulation outside of studs	100 mm polyisocyanurate	100 mm polyisocyanurate	100 mm polyisocyanurate
Wall effective thermal resistance	6.88 $m^2 \cdot K/W$	11.08 $m^2 \cdot K/W$	8.67 $m^2 \cdot K/W$
Basement wall insulation	100 mm polyisocyanurate	175 mm polyisocyanurate	175 mm polyuisocyanurate
Basement wall effective thermal resistance	6.54 $m^2 \cdot K/W$	10.48 $m^2 \cdot K/W$	10.48 $m^2 \cdot K/W$
Basement floor insulation	100 mm extruded polystyrene	100 mm polyurethane	100 mm extruded polystyrene
Basement floor effective thermal resistance	3.57 $m^2 \cdot K/W$	4.05 $m^2 \cdot K/W$	3.57 $m^2 \cdot K/W$
First and second story floor covering	50 mm lightweight concrete	50 mm lightweight concrete	50 mm lightweight concrete
South facade window area	10 m^2	10 m^2	10 m^2

While Table 4.9 gives an overview of the characteristics of the minimum life cycle energy use or cost single-family house envelope, many other configurations yield results within one percent of the optimal value results for each criterion.

For LCC, 368 configurations return a value within 1% of the minimum (i.e. less than $248,609) and 103 configurations yield a LCE value within 1% of the minimum (i.e. less than 1,510,153 MJ).

For the 0.5 value of the weighting factor *w1*, each objective function (LCC and LCE) was allowed to vary within 1%. Table 4.10 presents the design characteristics that are shared by more than 90% of envelope configurations within 1% of the optimum for each objective function. When no characteristic was dominant enough to meet the 90% criterion, the table indicates "No general tendency"

Table 4.10 – Design trends for three objective functions

	$w_1 = 1$ *(minimum LCC)*	$w_1 = 0$ *(minimum LCE)*	$w_1 = 0.5$
Roof total insulation thickness	150-225 mm	200-225 mm	150-225 mm
First roof insulation layer	No general tendency (no min. ratio)	Polyisocyanurate (min. 40% thickness)	No general tendency (no min. ratio)
Second roof insulation layer	No general tendency	No general tendency	No general tendency
Wall cavity insulation thickness	75-175 mm	250 mm	150-250 mm
Wall cavity insulation	Fibreglass batts	Blown cellulose	Mineral fiber or fibreglass batts
Wall insulation thickness outside of studs	100 mm	100 mm	75-100 mm
Wall insulation outside of studs	Polyisocyanurate	Polyisocyanurate	Polyisocyanurate
Basement wall insulation thickness	100-175 mm	175 mm	125-175 mm
Basement wall insulation	Polyisocyanurate	Polyisocyanurate	Polyisocyanurate
Basement floor insulation thickness	75-100 mm	100 mm	75-100 mm
Basement floor insulation	No general tendency	No general tendency	No general tendency
First and second story floor covering	50 mm concrete	Concrete	50 mm concrete
South facade window area	10 m^2	10-18 m^2	10 m^2

Table 4.10 also highlights the major differences and similarities between the optimal design conditions obtained based on the life cycle cost and life cycle energy minimization. The most important difference is the required thermal resistance for outside walls: LCC optimization leads to smaller thickness (75-175 mm) and the use of fibreglass batts for cavity insulation, while LCE optimization requires maximum thickness of cellulose considered in this study (250 mm) with double-stud walls. Both objective functions lead to the use of 100 mm thick polyisocyanurate for outside stud insulation. The reason for this divergence is that the cost of extra insulation materials, once the optimal point found for minimum LCC is passed, is not paid back in terms of energy cost savings over the life cycle. On the other hand, minimizing LCE calls for much higher levels of insulation because the embodied energy of the extra material is recuperated in terms of operating energy savings over its life cycle.

However, some envelope components are similar, whether aiming at a low LCE or LCC: concrete floors perform better than wood floors, smaller windows are preferred and polyisocyanurate is more effective for outside stud insulation. On the other hand, the second insulation material for the roof and the basement floor insulation material is of little consequence for both criteria. It can be observed that the wall outside of studs insulation thickness is smaller for w1=0.5 than for both minimum LCC and minimum LCE optimization. The fact that its value is not in between the values of minimum LCC and minimum LCE can be explained by the random component of the optimization algorithm. Indeed, it is possible that while exploring the search domain, some particles were stuck in a zone of thinner outside stud insulation for a few generations. While the 100 mm thick outside studs insulation is still dominant in the best results, enough envelope configurations with a 75 mm outside stud insulation.

Some conclusions about materials can also be drawn from those results. For instance, polyisocyanurate is superior to polyurethane for outside stud insulation, because it is less expensive, has a higher thermal resistance and a lower embodied energy. It is also to be preferred to extruded polystyrene from both a LCC and LCE point of view. Fibreglass batts and mineral fibre are the most cost-effective materials for cavity insulation, while blown cellulose minimizes life cycle energy.

4.5. Design applications

Figure 4.2 shows the position of optimal solutions on a LCC vs. LCE cartesian graph, with comparison to the initial design. The initial envelope design was suggested with the idea of achieving a higher thermal resistance than that required by the Quebec regulations in effect at the moment (Gouvernement du Québec, 1992), using common building techniques and materials, but with no intent of optimizing energy or cost on a life cycle basis.

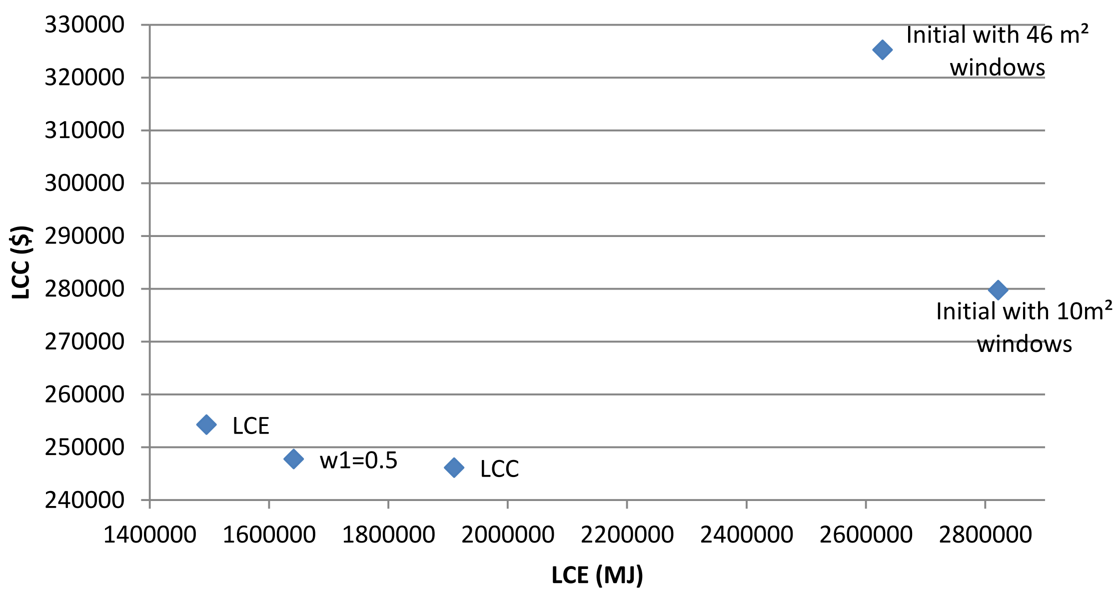

Figure 4.2 – Optimal solutions and initial design

The initial design is surprisingly far from both LCC and LCE optimum. The main reason for the large difference in terms of cost is that the house was designed with a fully glazed south facade

(46 m²), which is a very popular feature for houses built in a natural environment, as this is the case for the house. However, windows are expensive (especially from a life cycle perspective, as they need to be replaced every 25 years or so) and only so much passive solar energy can be gained through them. As a point of comparison, 1 m² of insulated wall for the initial design has an average LCC of $311.26, while 1 m² of triple-glazed window has a LCC of $1,685.49. The same house, with only 10 m² of south facing glazing, would perform much better and have a LCC of $279,753 and a LCE of 2,821,738 MJ. The LCE value is slightly higher because a house with moderate insulation, like the initial design, would benefit from larger windows to reduce its heating load.

Another piece of useful information that can be extracted from the results is the investment cost required for each configuration. As many configurations yield similar results in terms of LCC and LCE, the builder can choose one with the lowest investment cost within this selection. By reducing the selling price by a few thousands for a similar life cycle economical and energy performance, it is possible to make a house more attractive to customers in a competitive market. For example, the initial investment required for the minimum objective function value when w1 equals 0.5 is $174,780, but that value can be lowered to $165,399 while staying within a 1% variation of the criterion.

4.6. Comparison with previous results

While great care was taken to create an energy model that is accurate (including framing and thermal bridging effects) and to use pricing data as reliable as possible, perhaps the parameters that have the largest impact on results are the economical assumptions. Indeed, the optimal levels of insulation presented in this article are higher than those required by building energy efficiency codes such as the MNECH, which is also based on LCC optimization. A comparison of effective thermal resistance values of the optimal LCC envelope, as presented in this study, with codes and regulations from Canada is given in Table 4.11. In this table, the effective thermal resistances for Québec regulations (effective at the time this optimization was conducted) and Novo-Climat (new regulation in effect August 2012) are calculated using the same thermal bridging calculation method as for the modelled house (parallel heat flow according to ASHRAE 2009). It is to be noted that MNECH is currently under revision.

Table 4.11 – Comparison of effective thermal resistance values for minimum LCC with codes and regulations

	Previous Québec regulation	**Novo-climat (new regulation)**	**MNECH 1997**	**Min. LCC**
Above-ground walls ($m^2 \cdot K/W$)	2.32	2.53	4.1	6.88
Roof ($m^2 \cdot K/W$)	3.75	4.28	5.2	3.92
Basement walls ($m^2 \cdot K/W$)	1.51	1.77	3.1	6.54
Basement floor ($m^2 \cdot K/W$)	-	0.88	1.08	3.57

The higher thermal resistance values obtained in this study for minimum LCC are due in part to the longer study period, as well as to a low discount rate, which gives a considerable value to energy cost savings obtained many years in the future. This table suggests that if regulations and standards considered a life cycle that is closer to that of an actual house (ie. more than 30 years), as well as a lower discount rate, which would be more representative of the real value of future energy cost, they would tend to recommend higher levels of insulation.

Another optimization run for LCC was conducted to assess the impact of the chosen electricity cost escalation rate on the results; Tables 4.12 shows the impact of the selected energy cost escalation rate on the for minimized LCC.

Table 4.12 – Comparison of design trends for minimal LCC for two energy cost escalation rates

Energy cost escalation rate	*2%*	*0%*
Roof total insulation thickness	150-225 mm	150-225 mm
First roof insulation layer	No general tendency (no min. ratio)	Polyisocyanurate (0 to 60%)
Second roof insulation layer	No general tendency	No general tendency
Wall cavity insulation thickness	75-175 mm	75-150 mm
Wall cavity insulation	Fibreglass batts	Fibreglass batts or mineral fibre
Wall insulation outside of studs thickness	100 mm	75-100 mm
Wall insulation outside of studs	Polyisocyanurate	Polyisocyanurate
Basement wall insulation thickness	100-175 mm	100 mm
Basement wall insulation	Polyisocyanurate	Polyisocyanurate
Basement floor insulation thickness	75-100 mm	75-100 mm
Basement floor insulation	No general tendency	Extruded polystyrene or polyurethane
First and second story floor covering	50 mm concrete	50 mm concrete
South facade window area	10 m^2	10 m^2

The design trends for configurations within 1% of the objective function remained essentially the same, with a small increase in insulation thicknesses. It can therefore be concluded that the choice of the escalation rate had a rather limited impact on the results. While all values used in this economical analysis seem reasonable to the authors, their variation in the future remains uncertain.

4.7. Discussion about the life cycle analysis methodology

While scientific literature available about LCA of buildings is growing at a fast pace, there is still a lot of discussion regarding the methodologies to be employed and their possible flaws. Therefore, the author deems necessary to explain the choices made in the methodology for this thesis, and their impact on the validity of the conclusions. The objective of this is to bring attention to uncertainties, in order to increase transparency, credibility and acceptance to the LC aspect of this work, as advocated by Huijbregts et al. (2003). As pointed out by various studies, the main issue of contention for LCA is the embodied energy inventory data (Blengini and Di Carlo, 2010, Dixit et al., 2010, and Sartori and Hestnes, 2007). This short discussion aims at pointing out the most common sources of uncertainties in embodied energy inventory, and to present the properties of the inventory data used in this thesis.

First of all, the choice of the life cycle boundaries may vary from one study to another. Dixit et al. compares many definitions as proposed by different authors. For example, Crowther's definition (1999, as quoted by Dixit et al.), "the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings.", does not clearly state if extraction and transportation of raw materials are included in the manufacturing process, and excludes all post-operation phases. Other definitions are more precise, such as "the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building", which is employed in five articles (as cited by Ding, 2004). It is to be noted that recycling is not taken into account in the previous definition.

Sartori and Hestnes (2010) highlight in their research that many studies do not state if energy data is provided in primary or secondary energy. They define primary energy as including extraction, transformation and distribution losses; however, other authors exclude resource extraction from the primary energy calculation (Crawford et al., 2002). Also, Sartori and Hestnes point out that embodied energy may or may not include feedstock energy. Feedstock energy is the heat of combustion of raw material, or their potential to produce thermal energy when burned. The reason to consider this value is that, by using material in a building, a choice is made not to use its potential to provide energy by combustion, and therefore represents the loss of a source of energy.

Another source of potential misinterpretation of the results is the methodology used to obtain embodied energy inventory data. Three main methods are used: process-based, input/output analysis and hybrid analysis (Dixit et al., 2010). Some other sources mention statistical analysis, but it is not detailed here. The process-based method consists in breaking down a product into all the upstream processes required to manufacture the product, including all resource inputs. The most important limit of this approach is its intrinsic incompleteness; it is practically impossible to go cover a complete system boundary. The second approach, the input/output method (IO), uses economical input/output matrices to quantify the resource flows of sectors of the industry and to evaluate the environmental impact of processes and products (Hendrickson et al., 1997). While the IO method boundaries are practically complete, its main flaw is that it could be unreliable because of “assumptions regarding tariffs and the homogeneity and proportionality of sectors” (Treloar, 1997). Hybrid methods are by definition a combination of both process-based and IO-based methods; they attempt at using the best features of each of them. However, this method is seldom applied in studies or databases.

Of course, the age and geographical location of data also has a major impact its accuracy. One can think of the different energy mixes; in Québec, the predominance of hydro-electricity increases the efficiency of electricity production and therefore the ratio of secondary to primary energy use. Technologies used by the industry might also vary, as would transport distances.

Under this light, it is interesting to be aware of the source of data provided by the Athena Impact Estimator, as it is used for most building embodied energy calculations in this thesis. Athena's data is expressed in primary energy units, and includes the following phases of the life cycle: manufacturing, transportation, construction and demolition processes including on-site construction of building assemblies, maintenance, repair and replacement effects through the operating life, and demolition and disposal. Moreover, "Athena's databases are regionally sensitive, taking into consideration manufacturing technology, transportation and electricity grid differences as well as recycled content differences for products produced in various regions.", according to the ASMI's website (Athena Sustainable Materials Institute, 2012). These characteristics attest of the quality of the LC inventory data provided by the Athena Impact Estimator. Nevertheless, Optis (2005) states that Athena uses process-based LCI methodology, based on his personal communications with an Athena Sustainable Materials Institute staff member (it is not clearly stated in the documentation available in the program). This methodology, as explained above, can lead to incomplete data. Also, the age of data is analyzed from the source list given in ASMI's "Athena Impact Estimator for Buildings V 4.1 Software and Database Overview"; it is found that, for example, all insulation materials data dates from 2002. It is difficult to assess how the manufacturing processes and energy sources have changed in the past 10 years. In conclusion, while ASMI's data could be improved in terms of inventory methodology and age of data, it is applicable to Canadian building industry, and is deemed being "amongst the most mature" LCI databases in the world (Newton et al., 2009).

Other sources are used in cases where ASMI's database does not offer data for certain materials. This is the case for sprayed polyurethane; while this material is becoming more and more popular for residential buildings in Québec, the author was unable to obtain embodied energy data for North American. Consequently, the work of Petersdorff et al. (2002), which applies to continental Europe, is used to obtain a value of embodied energy for this material. The value is given in terms of “non-renewable primary energy demand for production”. The detailed methodology used to calculate this value is given in another report from 1999, which the author was unable to access. While this data is about as old as what is available in Athena, and is given in primary energy, the different geographical location may have a significant impact on the value of embodied energy. Furthermore, it does not include energy use for the end-of-life life cycle phase.

Because the uncertainty concerning this value is rather high, and because insulation material embodied energy has a large impact on the results of the life cycle energy optimization conducted in this thesis, a sensitivity analysis on the embodied energy value of sprayed polyurethane is carried out and presented in this section.

The LCE optimization is conducted again for values of polyurethane embodied energy that correspond to -30%, -15%, +15% and +30% of the used value in the previous analysis (4446 MJ/m^3). It is found to have very little impact on the general guidelines for minimizing the LCE.

The only parameter that changes is the basement floor insulation, where sprayed polyurethane is preferred to the other option, extruded polystyrene, when its embodied energy becomes close to that of the polystyrene (3112 vs 2918 MJ/m^3). It is assumed that this would not have a major impact on the LCC and LCE of the optimal houses, since the basement floor covers a small area compared to other walls and roof. Therefore, the author concludes that the uncertainty related to the embodied energy of polyurethane is not an issue that leads to significant error in the optimization of LCC and LCE for the house envelope.

4.8. Summary

A systematic optimization process was conducted on various building envelope variables to minimize both LCE and LCC for a lifespan of 50 years. Results show that, even for LCC minimization, the required levels of insulation are higher than of those recommended by programs such as Novo-Climat and MNECH.

While the results obtained for the envelope are optimal for this specific house, they are obtained for a simple HVAC system; that is, with electric baseboard heaters and cooling with a reference system with a COP of 3. It may be more cost and energy effective, past a certain point of envelope thermal resistance, to invest in HVAC systems (such as heat pumps or solar collectors) rather than in further insulation to obtain an even lower LCC or LCE.

5. Modeling of mechanical systems

While optimizing the envelope is the first step to take in the design process of a low-energy house, the importance of the mechanical systems should not be underestimated. Indeed, some researchers have found that mechanical systems have a greater impact than envelope design on the reduction of life cycle primary energy use (Gustavsson and Joelsson 2010).

Consequently, the LCC optimal envelope is selected and a variety of mechanical systems are designed and modeled for this house. Because some of the considered systems are rather complex and have a performance that depends on numerous factors, they are modeled in TRNSYS, to take into account detailed sub-hourly performance. Special attention is given to the design process of the mechanical systems. While in most residential applications, rules-of-thumb are used for design, it is believed that for low-energy houses, better calculation methods and transient simulations, such as TRNSYS, should be used (Kummert and Bernier 2008).

This chapter presents the selection of mechanical systems as well as the design methods used and their detailed models in TRNSYS. This chapter is inserted in the thesis for two reasons: (1) to explain the complexity of simulation of HVAC systems, and (2) to help future students in the development of similar or even more complex systems.

5.1. Selection of mechanical systems to be studied

Mechanical systems are studied on two bases: their performance for heating only, and their performance for heating and cooling. The reason for this choice is that, for the climate of the region selected for this study, the cooling loads are very small and make air conditioning unnecessary; however, many customers will require air conditioning in their homes to attain their high comfort expectations.

Mechanical systems to be studied in this thesis are chosen based on previous research as well as on practical considerations, such as comfort, market penetration and adaptability to different owners' needs. For space conditioning, electrical baseboards (for heating only) and central conditioning unit with electric resistance coil (for heating and cooling), an air-source heat pump, an air-source heat pump for cold climates and a ground-source heat pump are considered.

A heat recovery ventilator (HRV) is considered on the outside air stream to reduce the energy use for heating of ventilation air.

Domestic hot water is obtained through an electrical hot water tank, with the possibility of adding a flat-plate solar collector or a desuperheater if using a ground-source heat pump. Desuperheaters are not considered for air-source heat pump because no data was available from manufacturers for those systems.

Figure 5.1 presents all the modeled systems which were considered to meet space heating and cooling as well as domestic hot water needs. Systems 1-2 are modeled for the case where only heating is evaluated, while systems 3-4 are the equivalent for the case where both heating and cooling are evaluated. Systems 5 to 11 use the same computer model for both cases.

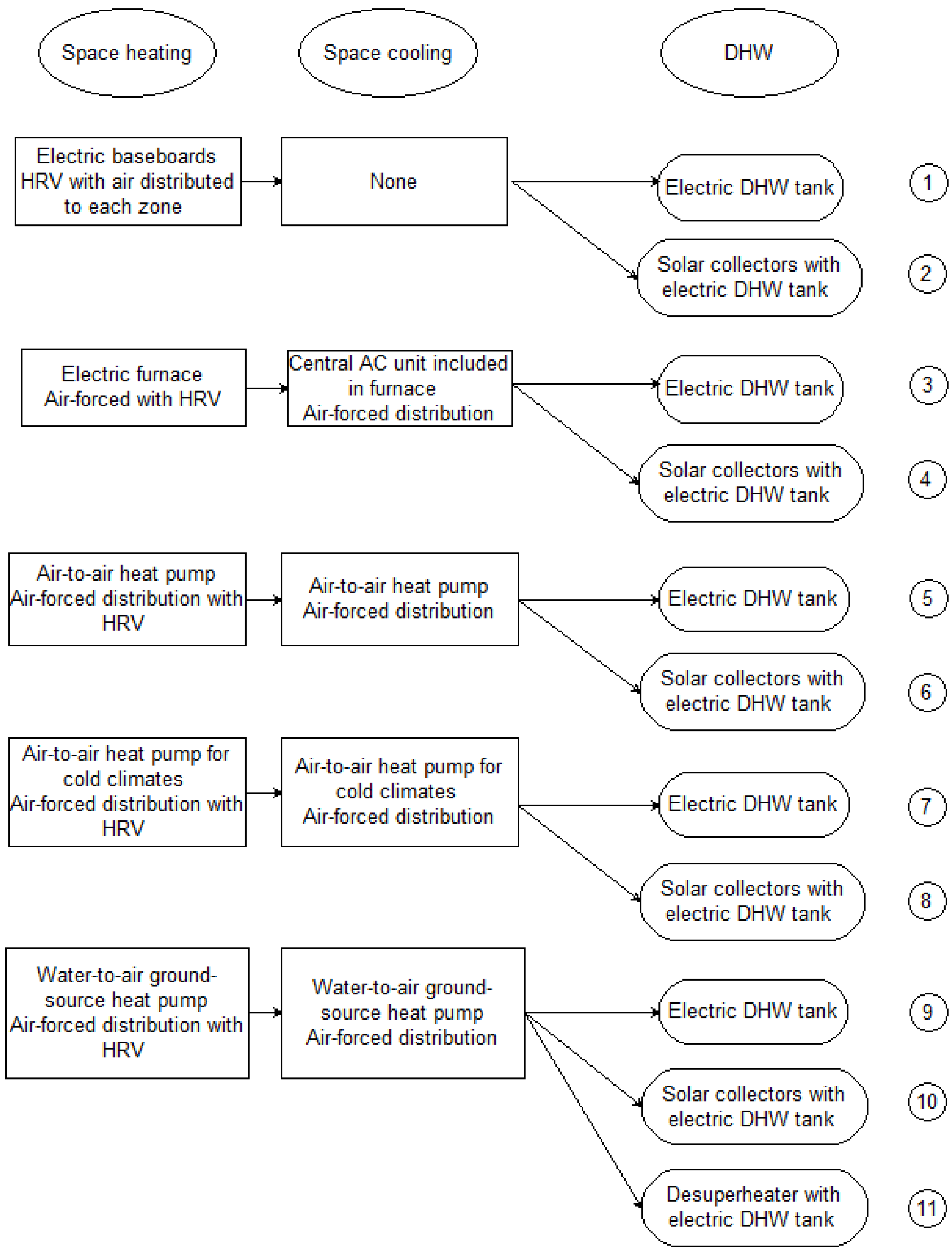

Figure 5.1 – Studied combinations of space conditioning and DHW equipment

The following paragraphs explain the reasons for the selection of the mechanical systems. They include the results of previous studies from the scientific literature, as well as performance data taken from technical literature and practical consideration.

Electrical baseboard heating is used as a base case comparison as it is the most common heating system in Québec.

Air-to-air heat pumps are a common technology in Canada, as they can provide both heating and cooling, at a lower investment cost than a geothermal system. However, standard air-source heat pumps are not designed to operate at typical winter outside temperatures in Québec; below temperatures of about -10°C, they are usually turned off and a backup heat source is used, consequently reducing the seasonal efficiency of this equipment. For this reason, a new generation air-source heat pump, which can provide better COP at low temperatures, is also investigated here.

It was shown that ground source heat pumps can contribute to GHG emission reduction (Saner et al., 2010 and Zmeureanu and Wu, 2007), as well as being one of the system that uses the least primary energy (Gustavsson and Joelsson, 2010). It is also a technology that is well understood and that is available from most HVAC equipment distributors.

While an electric DWH tank is the most common way to provide hot water in Québec, Biaou and Bernier (2008) demonstrated that solar thermal collectors with an electric backup was the best way to achieve net zero energy consumption for the domestic hot water system in Montréal. However, a desuperheater is also considered in this study even if it was proven not to be optimal for a net zero energy house by Biaou and Bernier. Because the objective of this study is rather to achieve a low LCC and LCE for the whole house, optimal solutions might differ from those for a net zero energy house. Moreover, the extra cost for a desuperheater is significantly lower than a solar thermal collector, when already using a heat pump. For solar collectors, a pre-heat tank is added according to recommendations from specialists (Natural Resources Canada, 2003).

Some systems were excluded for practical reasons. For example, a wood pellet heating system could be efficient, but since some houses in the project will be used as secondary homes, it would not be convenient to let the system run without surveillance during the week.

Other design considerations led to the choice of specific features for the space conditioning and domestic hot water systems. For all heating systems except electric baseboards, distribution of heat is achieved through a forced-air system. This choice is made because the project developer wished to use a single system to deliver both heating and cooling, which allows for a house owner to add air conditioning, if it was not included in the initial house, without any major renovations. In order to have comparable cooling systems, electrical heating is coupled to a central air conditioning system, even if a ductless AC system could be less expensive and seems to make more sense. The reason is that heat pumps used for heating will be able to deliver zoned air conditioning, and air dehumidification, something that a single ductless AC unit cannot achieve. Therefore, the author decided that it would not be reasonable to compare costs and energy consumption of systems that do not provide the same service.

In the case of ground-source heat pump, water-to-air or water-to-water heat pumps were both an option. Because the house is to be air conditioned, a forced-air distribution system seems to be a better option than low temperature hydronic radiators or radiant floors, to avoid extra investment costs. Indeed, even if a water-to-water heat pump is usually around $1000 less expensive than a water-to-air, the addition of low temperature hydronic radiators would cost about $4000 (based on prices for Smith's Environmental Heating Edge radiators, as estimated by the distributor), and radiant floors also require an investment of many thousands of dollars. Furthermore, water-to-air heat pumps available on the Canadian market present better coefficients of performance than water-to-water ones. Typically, a dual stage water-to-air ground source heat pump with an entering source temperature of 4°C and a entering air temperature of 21°C yields a COP of 4 to 4.5, while a dual stage water-to-water ground source heat pump with the same entering source temperature of 4°C an entering water temperature of 38°C (assumed return temperature from the bottom of a stratified storage tank) offers a COP between 3.5 and 4. Dual-stage heat pumps are considered for this application because they offer better comfort and lower cycling rate, which in turn increases the life expectancy of the equipment. Moreover, the cooling loads are much smaller than the heating loads in this study house; using a heat pump sized for heating to cool the house during summer would result in high cycling and temperature variance.

5.2. Detailed loads for the selected house envelope

The composition of the minimum LCC envelope selected for the evaluation of mechanical systems is detailed in Section 4.4 of Chapter 4. Tables 5.1 and 5.2 and Figure 5.2 and 5.3 present the heating, cooling and DHW loads for this envelope, for either a steady temperature set point or a night setback temperature. The ground-source heat pump operated with a daily steady set point (at 21 °C), while other systems can accommodate a night setback (at 18°C in heating mode). The reason why the GSHP uses a steady set point temperature is that the high power demand required when switching to the day set back has a large impact on the borehole sizing. A more sophisticated control strategy, using a back-up electrical resistance element for this purpose, could be implemented, but this level of control complexity is beyond the scope of this work.

Table 5.1 – Heating, cooling and DHW loads for the minimum LCC envelope (for steady set point 21°C heating, 24°C cooling)

Peak heating load	3.51 kW
Peak cooling load	2.14 kW
Annual heating load	6208 kWh
Annual cooling load	790 kWh
DHW load	4496 kWh

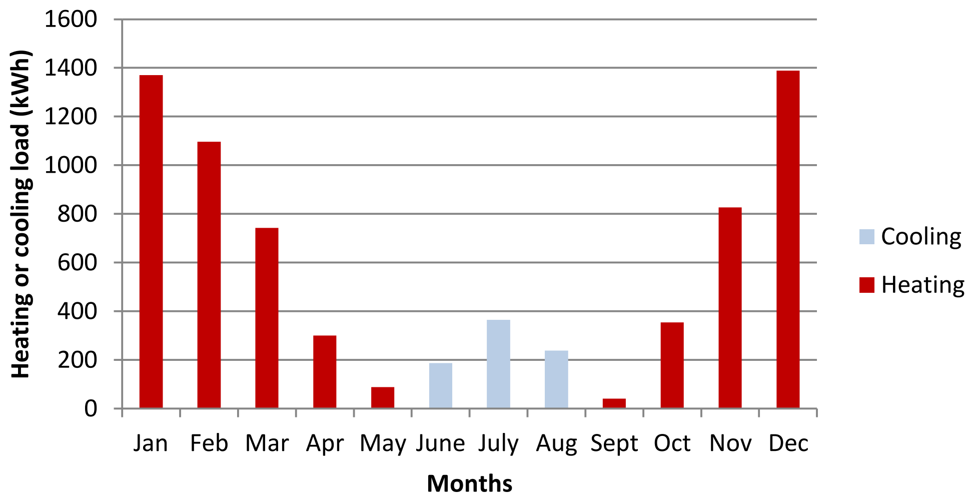

Figure 5.2 – Monthly cooling and heating loads for the minimum LCC envelope (for steady set point 21°C heating, 24°C cooling)

Table 5.2 – Heating, cooling and DHW loads for the minimum LCC envelope (for night setback 18/21°C heating, cooling 24°C)

Peak heating load	6.44 kW
Peak cooling load	2.14 kW
Annual heating load	5801 kWh
Annual cooling load	790 kWh
DHW load	4496 kWh

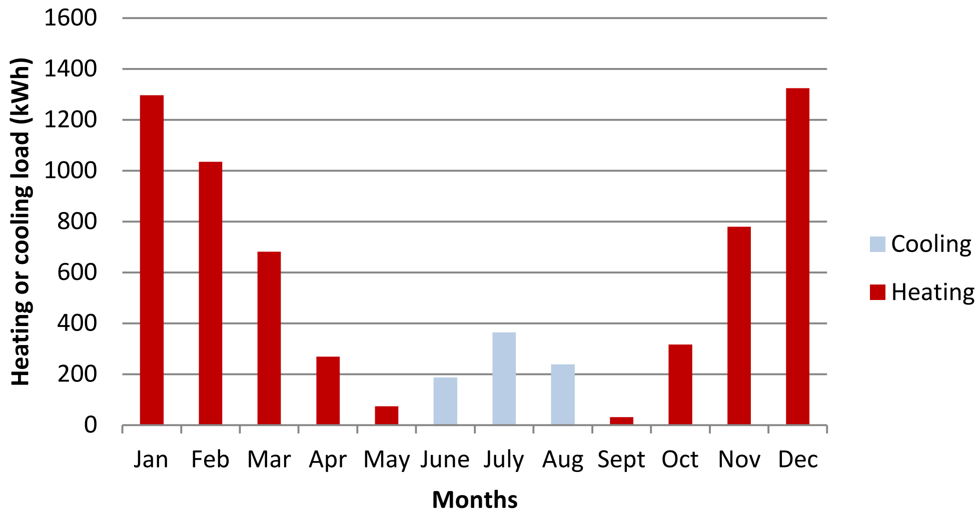

Figure 5.3 – Monthly cooling and heating loads for the minimum LCC envelope (for night setback 18/21°C, cooling 24°C)

5.3. Electrical heating with optional central air conditioning

5.3.1. Design

For the scenario where only heating is assessed, electric baseboards are sized based on simulated peak heating loads of the house for each of the three zones (basement, first floor and second floor) for a day setpoint of 21 °C, a night set point of 18 °C and a time step of 0.1 hr. Commercially available electric baseboards are then selected for each zone based on the obtained loads: 1500 W for the basement, and 2500 W for each of the first and second floors, for a total of 6,500 W. For the case where both heating and cooling are evaluated, an electric furnace (electric element combined to an air-conditioning unit) provides heating and cooling to the forced-air distribution system. Sub-hourly simulation results are also applied to size the air conditioning unit (with a constant set point of 24 °C), and it is found that a capacity of 2.14 kW is required. A commercially available central air conditioner is selected: an Energy Star certified York model TCGF18S41S3 (Johnson Controls, 2011), of the smallest capacity available (5.28 kW/1.5 tons) which has a SEER of 14.5. The heating element has a capacity of 6.5 kW, as for the electric baseboards.

5.3.2. Modeling

The same model is used for both the electrical baseboards in the heating only scenario, and the alternative with an electrical furnace which includes an AC unit, because the heating and cooling seasons do not overlap and therefore heating energy can be isolated from cooling energy in the same model. Figure 5.4 shows the difference between the model being used for (a) heating only and (b) heating and cooling scenarios, and (c) the actual systems.

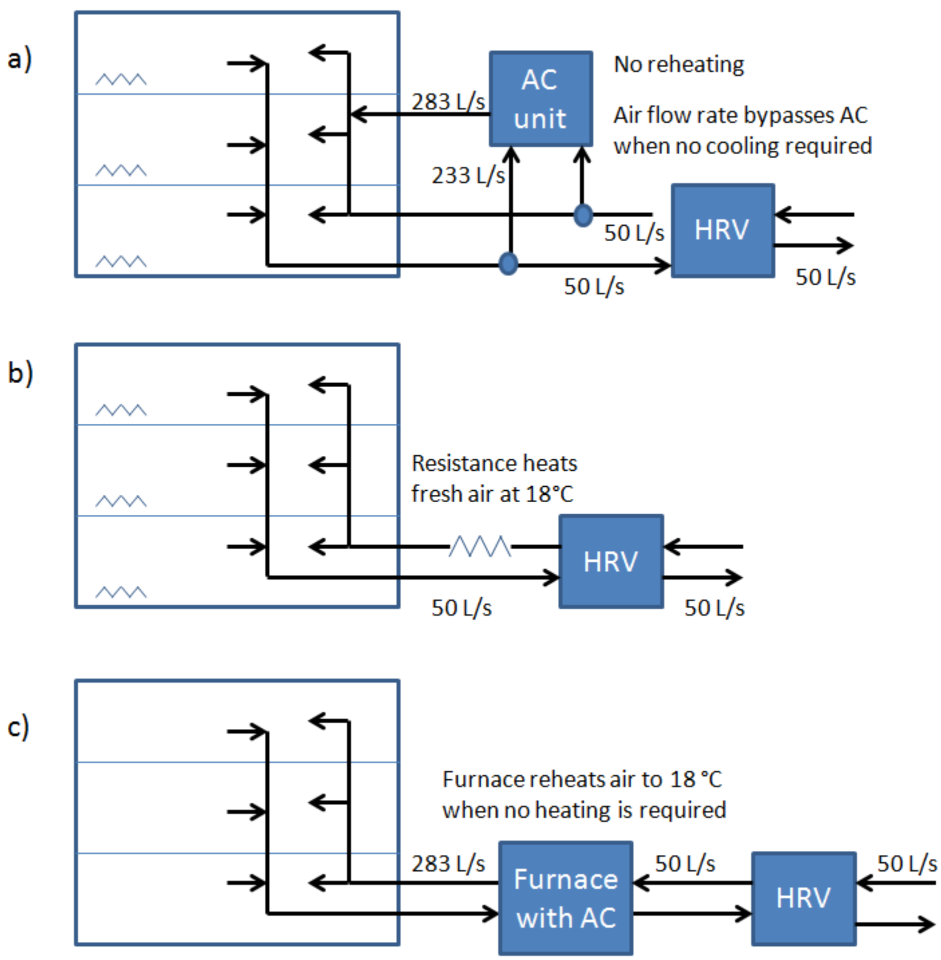

Figure 5.4 – Ventilation configuration a) as modeled b) as built for heating only c) as built for heating and cooling

The system is modeled as having electrical resistance heat gains in each zone, instead of in the air flow coming out of the furnace for the heating and cooling scenario (c). The assumption is made that this is approximately equivalent if the air flow is properly balanced to deliver the right proportion of air to each zone depending on its heat losses. Furthermore, the reheat element energy consumption is neglected because in the end, that extra load will be met by the baseboards in each zone.

Table 5.3 presents the Types used in the TRNSYS model, while Figure 5.5 shows the Types and their connections for the model.

Table 5.3 – Types used in the TRNSYS model of electrical heating with optional AC unit

Type	Description	Name used in Simulation studio
2	Differential Controller	Heatonb, Heaton1st, Heaton2nd and Coolon1st
33	Psychrometrics	Type33c and Type33e
56	Multi-Zone Building	Type56a
515	Heating and Cooling Season Scheduler	Type515
648	Air Mixing Valve	Type648-2
665	Air-Source Heat Pump	Type665
760	Sensible Air to Air Heat Recovery	Type760a
Equation block	Air flow properties for ventilation entering zones	Q_ventilation

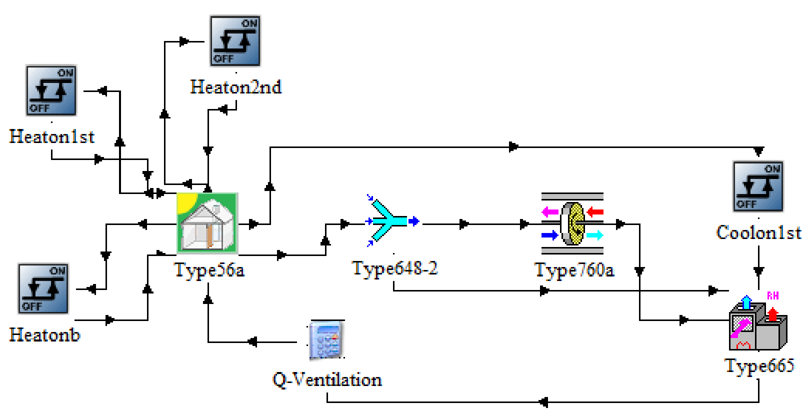

Figure 5.5 – TRNSYS model of electric heating with optional AC unit

Resistance heating baseboards are modeled using pure convective gains in each zone, and are turned on by the thermostat signal (Types 2). The gain power for each zone is defined as the rated power of the baseboard multiplied by the thermostat heating signal (which is 1 or 0, depending on the room temperature being lower or higher than the set point).

Type 648-2 represents the collection of used air from all three zones, at a rate of 50 L/s when the AC unit is off and 283 L/s when AC is on. 50 L/s is then sent to the heat recovery ventilator (Type760a) to heat an equivalent flow of entering fresh air and is then exhausted, and an extra 233 L/s is sent to Type665 when AC is on (as shown in Figure 5.4).

Type665 models the behavior of an air-source heat pump (the central air conditioning unit). During the cooling season, it is activated by the cooling signal coming from the differential controller Coolon1st, based on the temperature of the first floor. The incoming air properties are calculated from the respective properties of return used air (coming from Type648) and fresh air (coming from Type760). When the air conditioning unit is on, the used air flow rate is increased to provide 283 L/s of air, according to the manufacturer specifications. Type665 returns the properties of conditioned air (temperature and relative humidity), as determined by the performance table provided by the manufacturer. The performance table, available in Appendix C, is entered in a .dat file that can be read by Type665. Type665 has an internal routine that allows it to interpolate the performance of the heat pump depending on the conditions it operates in (indoor and outdoor DB and WB temperatures, as well as air flow rate). Table 5.4 gives the parameters used for Type665.

Table 5.4 – Type665 AC main parameters

Specific heat of air stream	1.007 kJ/kg·°C
Total air flow rate	283 L/s
Rated indoor fan power	75 W
Rated outdoor fan power	187 W

The results are sent to the Q_ventilation equation block, which calculates the flow rate and properties of the supply air entering the building zones, depending on its provenance (HRV or AC unit), and is in turn connected to Type56.

5.4. Air-source heat pump with electrical resistance back-up

5.4.1. Design

Because air-source heat pump efficiency drops quickly at low temperature, this system needs a back-up heat source. In this case, an electric resistance heating is chosen as a back-up. The control strategy used is that of the equilibrium point, meaning that the ASHP will provide all the heat until the outside temperature drops below -12°C, which is typically the minimum temperature at which heat pumps are designed to operate. When the outside temperature is below that point, the electric resistance will be used. A night setback is added to the temperature control, for a night set point of 18°C, that gradually increases to 21°C between 6:00 and 7:30 A.M. Therefore, a heat pump that is capable of meeting the heating load of the house at -12°C (about 5.5 kW, based on previous sub-hourly simulation results) is selected: a York model ASHP, the THJF, which in its smallest capacity available is a 1.5 tons (5.58 kW) heat pump. The auxiliary heating element meets the maximum heating load of the house, at 6.5 kW. A time step of 0.05 hrs is used for all heat pumps (air-source and ground-source) for more accuracy in control strategies.

5.4.2. Modeling

Table 5.5 presents the Types used in the TRNSYS model, while Figure 5.6 shows the Types and their connections for the model.

Table 5.5 – Types used in the TRNSYS model of an air-source heat pump system

Type	Description	Name used in Simulation studio
2	Differential Controller	Heaton1st and Coolon1st
33	Psychrometrics	Type33c and Type33e
56	Multi-Zone Building	Type56a
515	Heating and Cooling Season Scheduler	Type515
648	Air Mixing Valve	Type648-2
760	Sensible Air to Air Heat Recovery	Tyoe760a
	Re-heating electrical element for ventilation air	Reheat
Equation blocks	Air flow rate for heat pump	HP_airflow
	Air flow properties for ventilation entering zones	Q_ventilation

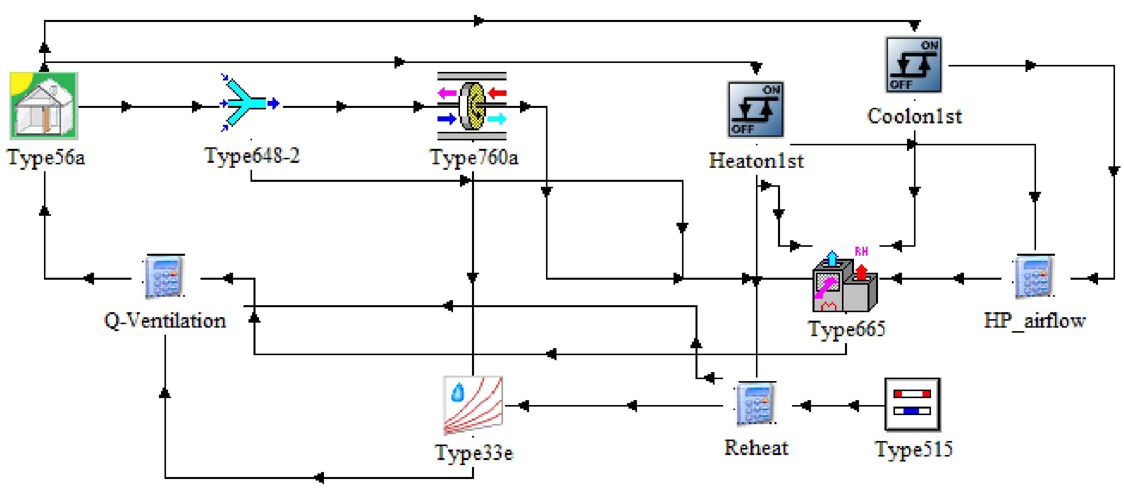

Figure 5.6 – TRNSYS model of an air-source heat pump system

The modeled air supply path is the same as shown in Figure 5.4 a), with the exception that the AC unit is replaced with an air-source heat pump. Type648-2 is used to mix return air collected from all three zones, and from that, 50 L/s is sent to the heat recovery ventilator (Type760a) and is then exhausted. When the heat pump is turned on, more air is drawn from all three zones to feed the heat pump. When thermostat indicate that no heating is required, fresh ventilation air coming out of the HRV is re-heated by an electric element, to avoid sending cool air directly to zones and consequently cause discomfort to the occupants. The re-heating element brings incoming air temperature to 18 °C, only during the heating season. Heating season indicator comes from Type515. The required power is calculated based on equation 5.1.

$$P_{reheat} = \dot{m}_{reheat} \cdot Cp_{air} \cdot (18 - T_{air\_in}) \quad \text{(Eq. 5.1)}$$

where P_{reheat} is the instantaneous re-heating element power in W, T_{air_in} is the incoming fresh air from HRV, in °C, $\dot{m}_{reheat}$ is the mass flow rate passing the reheat element, in kg/s. The specific heat of air (Cp_{air}) is 1005 J/kg·°C. P_{reheat} is integrated over the year to obtain the electrical consumption of the reheat element. Type33 is used twice to obtain the relative humidity of air leaving the reheat element. The first is used to acquire the absolute humidity of fresh entering air after it passed through the HRV; that value is passed on to the second Type33, which calculates the relative humidity based on the absolute humidity ratio and the temperature of the air after it has been reheated. The relative humidity can then be used in Type56. The HP_airflow equation block returns the control signal for the heat pump fan; it is set to 1 when heating or cooling is required, otherwise it is assumed that the ventilation bypasses the heat pump, as explained in section 5.3.2.

Type665 models the behavior of an air-source heat pump. It is activated by the heating or cooling signal coming from the differential controllers Heaton1st and Coolon1st, based on the temperature of the first floor, where the thermostat is installed. The incoming air properties are calculated from the respective properties of return air (coming from Type648) and fresh air (coming from Type760). Table 5.6 shows the main parameters used to define the York heat pump.

Table 5.6 – Type665 ASHP main parameters

Specific heat of air stream	1.007 kJ/kg·°C
Total air flow rate	283 L/s
Rated indoor fan power	75 W
Rated outdoor fan power	187 W
Auxiliary electric resistance heating	3500 W

The properties of cool or warm air exiting the indoor coil of the heat pump are sent to the Q_ventilation equation block: that block sends the properties of the air stream coming from the HRV/reheating element or from heat pump, depending on the status of the system, to the house model (Type56). The percentage of the air stream that is sent to each zone is found by trial and error to provide temperature as close as possible to the set point for both heating and cooling in all three zones: 35% to each of the first and second floor, and 30% to the basement. The same distribution proportions are used for the cold-climate air-source heat pump as well.

This model involves a simplification of the ventilation system in reheat mode (that is when heating is not required during heating season). Figure 5.7 shows, in the upper portion, how reheating of entering fresh air is modeled, while the lower portion illustrates the real setup of ventilation for reheating for a heat pump heating system. In the real system, the incoming ventilation air does not bypass the HP; instead, it goes through it and the air is circulated between the HP fan, which cannot operate at only 50 L/s. Consequently, the HP re-circulates 283 L/s of air, 50 L/s of which is fresh air, and an electric element reheats it to 18°C when needed.

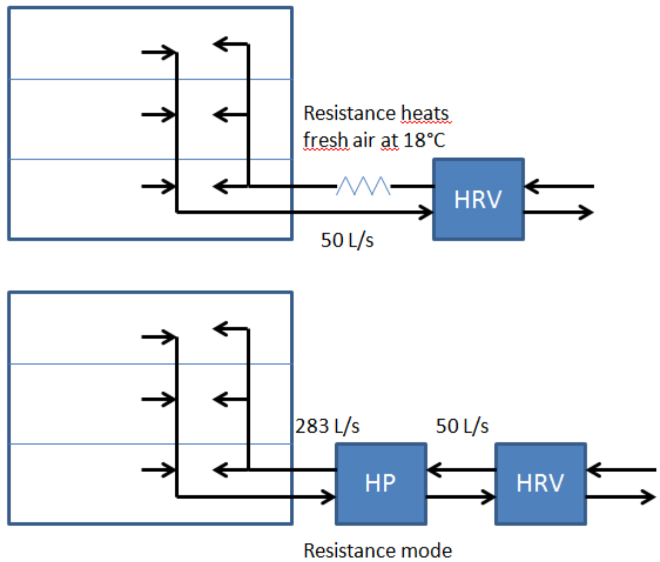

Figure 5.7 – Modeled vs. real configuration of air reheating with a heat pump

This simplification is assumed to have very little impact on the energy consumption since the extra air entering the heat pump would be approximately at the set point temperature. It is used for the other heat pump systems as well (cold-climate air-source and ground-source). When heating is required, air circulates between the HRV and the HP as shown in the lower section of Figure 5.7.

5.5. Cold-climate air-source heat pump

5.5.1. Design

The air-source heat pump selected for this study is designed specifically for cold climates: it has a variable speed compressor that increases its rotation speed when ambient temperature drops, in order to keep its heating capacity at a high level. Two heat pumps of this type are available on the market; the Mitsubishi Zuba Central and the Hallowell Acadia. Because the Zuba Central is significantly less expensive while still delivering enough heat for the needs of the house being studied here, it is preferred to the Acadia model. Moreover, the Zuba Central has a Variable Compressor Speed Inverter, which allows it to modulate its load to avoid cycling (Mitsubishi Electric Sales Canada, 2012). Because of that, even if that heat pump is available for residential applications in one size only (3.17 tons or 11.15 kW), it is expected that minimum cycling will occur.

5.5.2. Modeling

The model used for the cold climate air-source heat pump is the exact same as for the standard air-source heat pump, with the exception of the data file for Type665.

Complete technical information about the Mitsubishi Zuba is not available online. Only the heating and cooling capacity, temperature operating range as well as seasonal indicators for heating and cooling performance are given to give a general idea of the performance (Mitsubishi Electric Sales Canada, 2012), as presented in Table 5.7.

Table 5.7 – Specifications for the Mitsubishi Zuba Central

Cooling	Rated capacity	9.97 kW (34,000 Btu/hr)
	Rated input	2865 W
	EER	12.0
	SEER	15.00
System operating Temperature range – Cooling	Indoor	DB 19 °C to 32 °C WB 15 °C to 23 °C
	Outdoor	DB -18 °C to 46 °C
Heating	Max. capacity	11.73 kW (40,000 Btu/hr)
	Max. input	3670 W
	HSPF	9.4
System operating Temperature range – Heating	Indoor	DB 17 °C to 28 °C
	Outdoor	DB -30 °C to 21.1 °C WB -30 °C to 15 °C

Consequently, data for heating was obtained through personal communications with Mitsubishi Electric to evaluate the heating energy consumed by the heat pump; the heating capacity and electricity consumption for various outdoor DB temperatures are given in Appendix C.

However, the only information available for the cooling performance of the Zuba are those presented in the above table. While EER, SEER and HSPF are used by potential buyers to compare the relative performance of heat pumps they consider purchasing, studies have proven that those usual values cannot be used to evaluate absolute energy consumption and might even not be a good indicator of relative performance (Southern California Edison Design & Engineering Services, 2004). For example, EER is defined by the ratio of cooling capacity, in Btu/hr, to the power input required, in kW, typically for an indoor air DB temperature of 26.7°C and an outdoor air DB temperature of 35°C, which does not correspond to realistic conditions in Ste-Agathe-des-Monts. Because no performance data is available to conduct a sub-hourly simulation of the cooling energy consumption, it is assumed that it has a constant COP of 5. This assumption is based on results (presented in Chapter 6) that shows that, in this climate, the AC unit has a seasonal COP of 5.6; therefore, a slightly more conservative value is selected for the CCASHP. This assumption has a relatively low impact on the results, because the cooling load of the house is of only 796 kWh, compared to an annual heating load of 5801 kWh. Therefore, the annual energy consumption for cooling is 159 kWh, and equivalent to $12.48 in electricity cost. If the real average cooling COP was 4, the error would be 40 kWh or $3.14; if it was 6, the error would be of 26.3 kWh or $2.06. These potential errors are not significant enough to affect the final results.

The cooling and heating performance data is entered in a .dat file that can be read by Type665. Type665 has an internal routine that allows it to interpolate the performance of the heat pump depending on the conditions it operates in (indoor and outdoor DB and WB temperatures, as well as air flow rate). Table 5.8 gives the parameters used for Type665.

Table 5.8 – Type665 cold climate ASHP main parameters

Specific heat of air stream	1.007 kJ/kg·°C
Total air flow rate	472 L/s
Rated indoor fan power	75 W
Rated outdoor fan power	187 W
Auxiliary electric resistance heating	0 W

5.6. Ground-source water-to-air heat pump

5.6.1. Design

The heat pump sizing is based on the same peak loads as the electrical baseboards. Therefore a 7.0 kW heat pump (2 tons), the closest capacity available on the market, is required to meet the full loads. To meet this criterion, as well as other considerations outlined in Section 5.1, the selected heat pump is a Geocomfort XT series with a capacity of 2 tons. A complete performance table for this specific piece of equipment (Enertech Global, 2011) can be found at Appendix C.

Sizing of the borehole is conducted using the methodology and calculation spreadsheet developed by Philippe et al. (2010), with the objective of meeting the full heating load of the house. The completed spreadsheet can be found at Appendix D. It is to be noted that the methodology for a single borehole was used, even though two boreholes are needed; however, as explained by Philippe et al., the interaction between boreholes when the field consists of less than four of them is negligible. The values for maximum peak hourly ground load, monthly ground load and yearly ground loads come from the outputs of the TRNSYS simulation for the given house. The ground is assumed to consist mostly of gneiss, which is a common rock in the Laurentides region (the area north of Montréal where the house will be built); the average physical properties for this rock are taken from Kavanaugh and Rafferty (1997), and are summarized in Table 5.9.

Table 5.9 – Ground properties for boreholes

Ground conductivity	2 W/m.K
Ground heat capacity	2440 kJ/m³·K
Ground density	2649 kg/m³

The ground loop fluid is a propylene glycol solution, as it is the usual fluid for domestic geothermal systems in Québec. A volume concentration of 20% is selected to avoid freezing down to a temperature of -8°C (Engineering toolbox, N/A). The flow rate corresponds to what is recommended by the heat pump manufactured for closed ground loops at full load, which is 0.382 L/s (7 gpm). The resulting ground loop consists of one 83.9 m deep borehole.

5.6.2. Modeling and control

Because the TRNSYS component library does not include a two-stage water-to-air heat pump, multiple Types and equation blocks are assembled to simulate the functioning of the system. Table 5.10 lists the main components used to model the ground-source heating and cooling system, and Figure 5.8 shows the TRNSYS model.

Table 5.10 – Types used in the TRNSYS model of water-to-air GSHP

Type	Description	Name used in Simulation studio
2	Differential Controller	Heaton1st
15	Weather Data Processor	Type15
56	Multi-Zone Building	Type56a
504	Water-to-air Heat Pump	Type504-Stage1 and Type504-Stage2
557	Borehole (ground heat exchanger)	Type557d
648	Air Mixing Valve	Type648-2
760	Sensible Air to Air Heat Recovery	Tyoe760a
Equation blocks	Setpoint temperature for heating and cooling, with night setback	Tsetpoint
	Pre-heating electrical element for ventilation air	Preheat
	Air flow properties for stage 1 or stage 2 HP	HP_airflow
	Fluid flow properties coming from stage 1 and 2 HPs	HP_source_out
	Air flow properties for ventilation entering zones	Q_ventilation

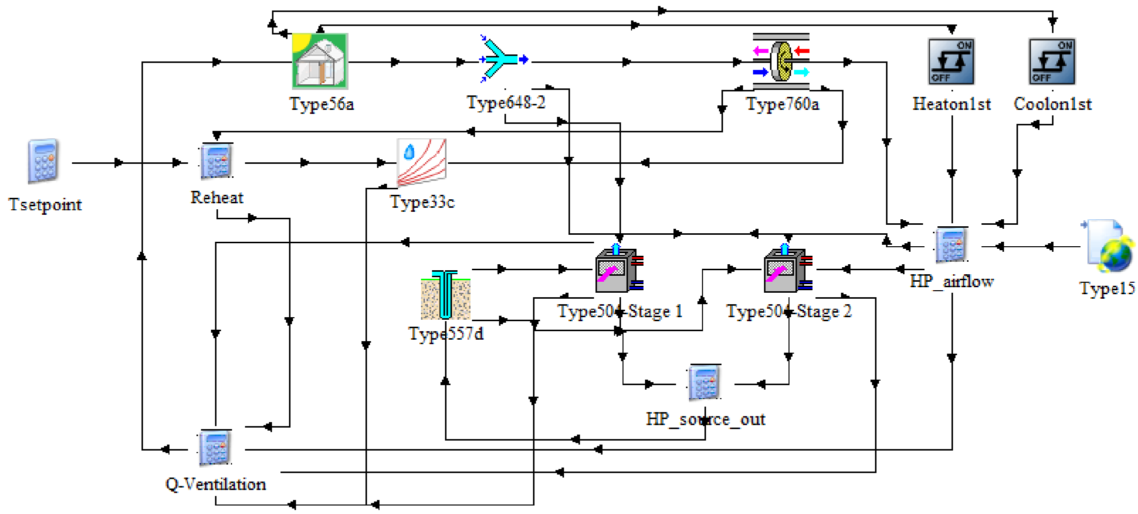

Figure 5.8 – TRNSYS model of a water-air GSHP system

The same HRV and re-heating model as for the ASHP is used. The HP_flow equation block uses the following conditions to determine if the heat pump is turned on in stage 1, stage 2 or if it remains off. If the thermostat (Heaton1st) indicates that the temperature is below the setpoint on ground floor, and the outside temperature is higher than the outdoor reset temperature of -10°C (from the weather data file read by Type15), stage 1 of heat pump is turned on. If heating is needed and the outside temperature is lower or equal to the outdoor reset temperature, stage 1 is turned off and stage 2 is activated instead. The reset temperature is chosen by trial and error, with the objective of meeting the heating load at all time, while minimizing cycling of the heat pump. While this control strategy may not be optimal, it still limits room temperature swings, when compared to a multi-stage thermostat (which activates stage 2 heating or cooling once the room temperature has dropped a given number of degrees below the set point). Some more sophisticated thermostats use fuzzy logic to predict the required amount of heat to keep a constant temperature, but the programming of such a thermostat is beyond the scope of this work.

The HP_flow equation block sends a binary (0/1) heating and cooling signal to each heat pump Type. Two identical heat pumps Type need to be used in this case because the TESS model used, Type504, does not allow to vary the air flow rate. Therefore, stage 1 heat pump is set for an airflow rate of 330.4 L/s (700 cfm), and stage 2 heat pump is set for 448.4 L/s (950 cfm), according to the Geocomfort heat pump model specifications. Each heat pump Type uses the same four external files to define their performance: one heating performance table, one cooling performance table, and one correction factors file for each heating and cooling. Correction factors are used in order to modify the output of the heat pump depending on the properties of the moist air entering the coil, and are taken from the manufacturer's catalog (Enertech Global, 2011). Both the GSHP performance tables and corrections factors are presented at Appendix C.

For stage 1, the liquid flow rate in the ground loop is 1401 kg/hr (6 gpm) and 1635 kg/hr (7 gpm) for stage 2. The properties of the ground loop liquid are outlined in Table 5.11.

Table 5.11 – Properties for the ground loop fluid

Volume concentration of propylene glycol	20%
Freezing point	-8 °C
Density	1027 kg/m³
Heat capacity	3.929 kJ/kg·K

Equation block "HP_source_out" is used to determine which flow of ground loop liquid is going to the borehole (ie. stage 1 or stage 2). The flow rate is the one coming from the stage in operation (therefore when $Flow_{HP1}$ is greater than 1 $Flow_{HP2}$ is close to 0, and vice versa). To obtain the temperature of that liquid flow, equation 5.2 is used.

$$FlowT_{borehole} = FlowT_{HP1} * gt(Flow_{HP1}, 1) + FlowT_{HP2} * gt(Flow_{HP2}, 1) \qquad \text{(Eq. 5.2)}$$

where $FlowT_{borehole}$ is the temperature of the liquid coming out the heat pump, in °C, and $Flow_{HP}$ is the liquid flow rate in kg/hr (HP1 for stage 1 and HP2 for stage2).

Type557, which mathematical model was developed by the University of Lund, Sweden (Hellström, 1989) is used to model the boreholes. This Type models the heat transfer between the fluid in the pipe and the surrounding soil. Heat transfer in the duct is convective, and conductive in the ground. The mathematical problem is solved using a combination of explicit finite difference method (numerical), and analytical method. Boreholes are vertical U-tubes; a vertical ground exchanger is selected to avoid any major disturbance to the soil, because the house is located on a wooded land. The piping is made of polyethylene. Figure 5.9 presents the configuration of one u-tube vertical borehole. It is to be noted that in this case, the system consist of two boreholes in parallel.

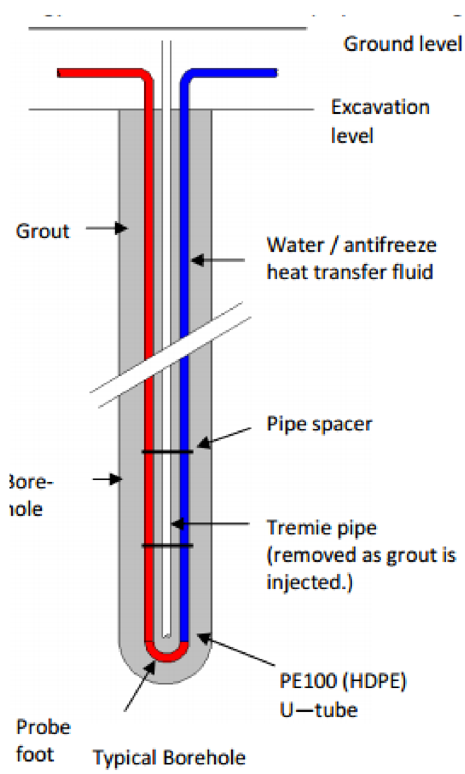

Figure 5.9 – Configuration of a u-tube vertical borehole (Source : Kensa Engineering)

The geometric parameters are defined by figure 5.10, and the main properties entered into the model are listed in Table 5.12.

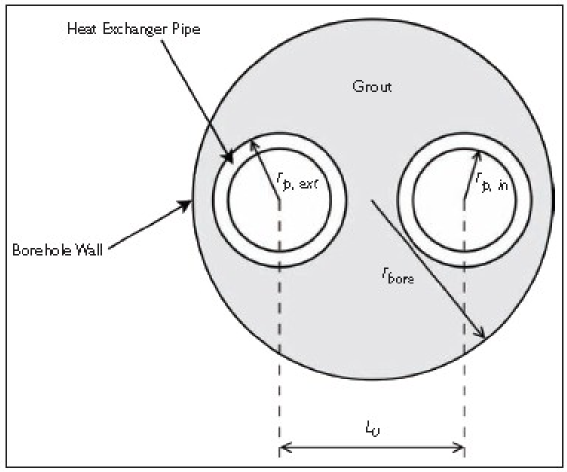

Figure 5.10 – Geometric parameters of a borehole (Source : Philippe et al., 2010)

Table 5.12 – Borehole model main parameters

Storage volume	2525 m³
Borehole depth	89.3 m
Borehole radius (r_{bore})	0.05 m
Number of boreholes	1
U-tube pipe inner diameter	0.0274 m
U-tube pipe outer diameter	0.0333 m
Pipe conductivity	0.42 W/m·K
Center-to-center distance between u-tube pipes (L_U)	0.058 m
Storage conductivity	2 W/m·K
Storage heat capacity	2440 kJ/m³·K

The storage is the volume of the ground affected by the heat exchange with the ground loop. It is assumed that ground temperature outside the storage follows the yearly variation of undisturbed soil temperature. As boreholes would be spaced by about 6 m if multiple boreholes were used (Philippe et al., 2010), the storage is calculated as a cylinder with a radius of 3 m with the same length as the borehole, resulting in a volume of 2525 m³.

5.7. Electrical DHW tank

5.7.1. Sizing

The electrical domestic hot water tank is sized to contain a full day of hot water usage; therefore, a 283 L (61.5 imp. gal.) tank is selected for a household of 4 persons (see the data for hot water usage in section 5.7.2).

5.7.2. Modeling

For all domestic water heating models, a time step of 0.1 hrs is used, to correspond to the available water usage profile data. The structure for the domestic hot water consumption modeling is presented in Figure 5.11.

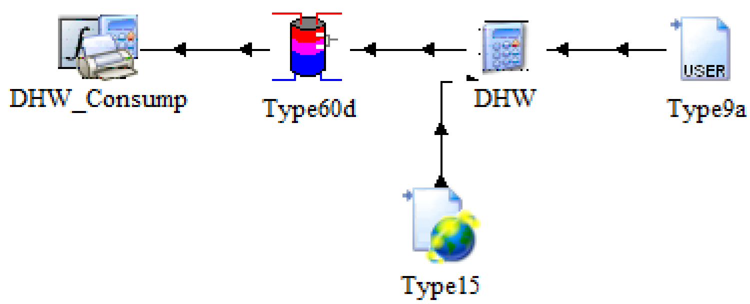

Figure 5.11 – TRNSYS modeling of DHW consumption

The DHW usage profile comes from the work of Jordan and Vajen (2001), who have created text files detailing annual DHW flow rates for a single family European home for three different time steps (1 minute, 6 minutes and 1 hour). Data has been adjusted to correspond to a Canadian average daily hot water consumption of 266 L, according to the research of Aguilar et al. (2005). Type 9 Data reader converts the text file into a usable input for other TRNSYS Types.

The DHW equation block converts flow rates in L/hr to kg/hr, assuming a water density of 998 kg/m³. It also calculates the temperature of incoming water from the city of Montreal mains, based on data published by Marcoux and Dumas (2004). Marcoux and Dumas provided weekly temperature measurements for five full years between 1994 and 2004; their data is averaged over this period for each week, and sinusoidal function is created to match the average points. It is assumed that because Ste-Agathe-des-Monts (the town for which weather data file is taken) is within 100 km of Montreal, this data is sufficiently accurate. The function is as described by equation 5.3:

$$T_{mains} = 10\sin\left(\frac{2\pi}{365}(Nday - 135)\right) + 12.7 \qquad \text{(Eq. 5.3)}$$

where *Nday* is the number of the day of the year (starting on January 1st). Figure 5.12 compares the data points with the approximate sinusoidal function used for city mains temperature. While the sinusoidal function slightly overestimates the temperature for most of the year, the maximum and minimum temperatures and the function period closely match the data point.

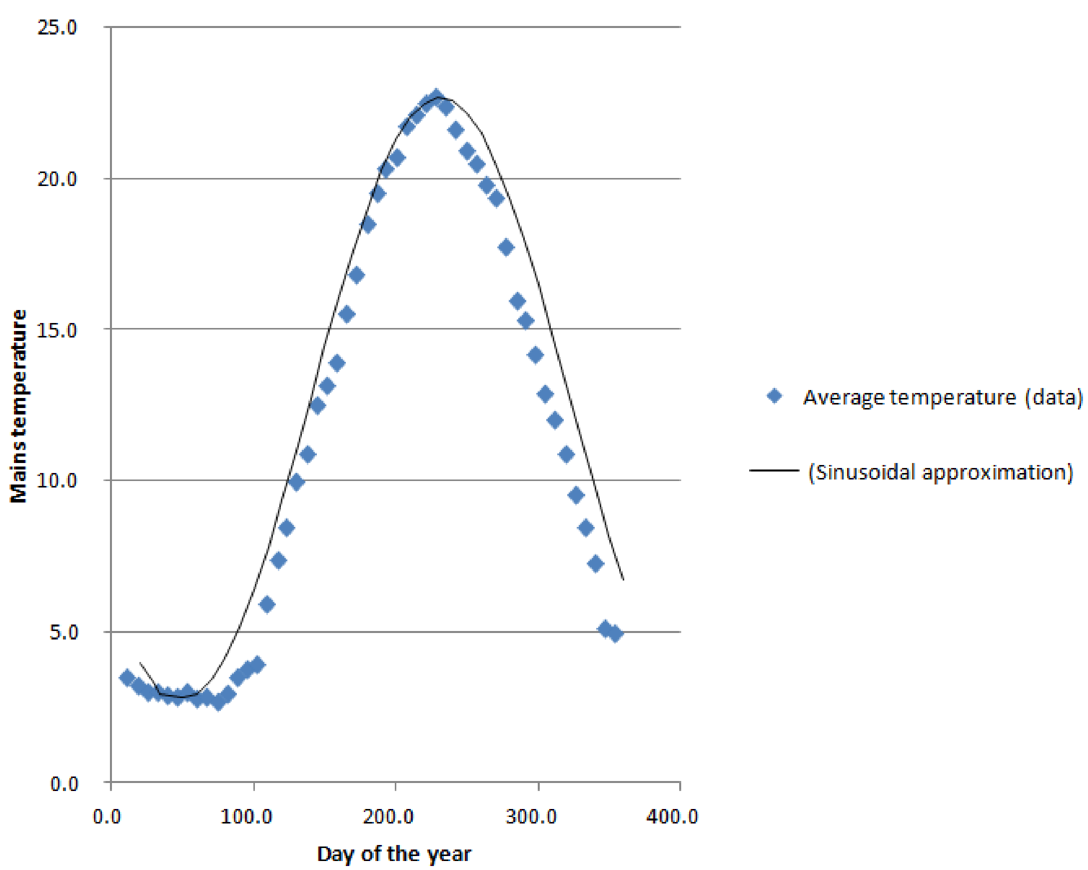

Figure 5.12 – Data used for water mains temperature

Type60 is then used to model the domestic hot water tank. The mass flow rate and the temperature of city mains as calculated by the DHW equation block are input into Type 60. Type60 considers the inlet flow rate to be equal to the outlet flow rate. Properties of the tank are based on Giant Factories' Super Cascade 9 model (Giant Factories, 2010). Table 5.13 outlines the tank's main characteristics, which are given as Type60 parameters, and Figure 5.13 presents the geometry of the tank.

Table 5.13 – DHW tank model properties

Tank volume	279 L
Tank height	1.52 m
Number of nodes for water properties	4
Heat loss coefficient	0.567 W/m²·K
Power of lower heating element	1500 W
Set point for lower thermostat	50 °C
Power of upper heating element	4500 W
Set point for upper thermostat	55 °C

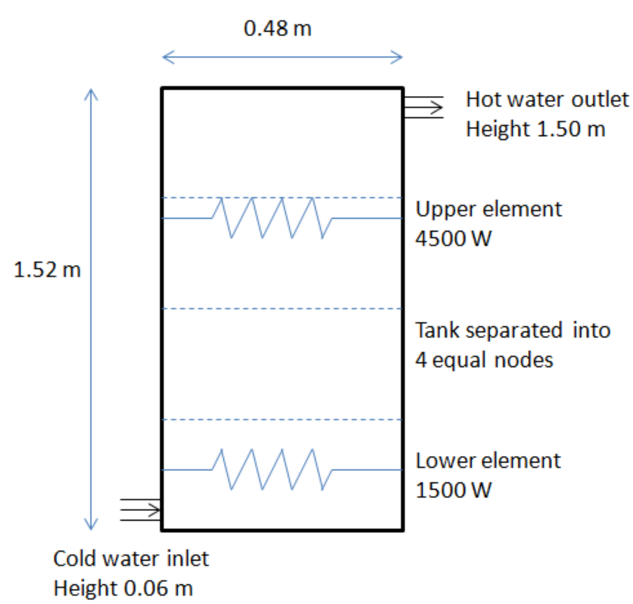

Figure 5.13 – Electrical DHW tank as modelled

The annual electricity consumption is calculated by integrating the electrical input of both elements over the full year, using Type 28.

5.8. Solar water heater with electrical back-up

5.8.1. Design

The solar water heater is designed using the same hot water loads as for the traditional electrical DHW water tank selection (section 5.5).

Three main types of solar collectors are available on the Canadian market: unglazed, glazed flat plate and evacuated tube collectors (Natural Resources Canada, 2003). Unglazed collectors are meant to be used for low-temperature applications, such as pool heating, and are therefore not suitable for domestic hot water. A glazed flat-plate collector is selected, because it was previously demonstrated that this type of collector is more cost efficient over its life cycle than evacuated tube collectors, for Montréal's climate and conditions (Leckner and Zmeureanu, 2011). The model chosen is the Heliodyne GOBI, and its standardized performances are available at Appendix C.

The selected system constitutes of a storage tank with an internal heat exchanger, coupled to a standard electrical domestic hot water tank. The propylene glycol solution flows from the collectors to the coiled tube heat exchanger to preheat water in the storage tank. When hot water is used by the occupants, the DHW tank draws preheated water from the storage tank instead of directly from the city mains, which reduces the electrical input required to keep the water at a temperature of 55°C. While the storage tank implies an extra investment cost, it is used to increase the efficiency of the system by ensuring that the propylene glycol solution exchanges heat with water at a rather low temperature instead of water that is kept at 55°C. Figure 5.14 illustrates the solar water heater system.

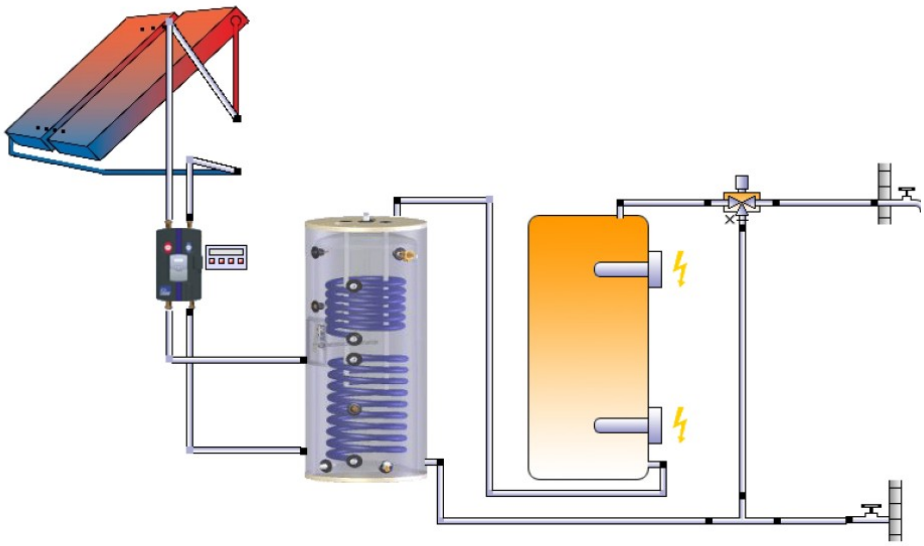

Figure 5.14 – Schematics of a two tank solar water heater system with internal heat exchanger (Credit : Les Entreprises écoSolaris inc.)

Because winter temperatures fall well below 0°C in Ste-Agathe-des-Monts, a propylene glycol and water solution is used as the heat transfer fluid. A volume concentration of 50% is selected to prevent freezing at temperatures down to -35°C (Engineering Toolbox); see Table 5.3. As propylene glycol is non-toxic, it is safe to be used in heat exchangers in contact with drinkable water.

Installers as well as experts (such as in Resources Canada buyer's guide, 2003) make recommendations concerning the proper sizing of the system, in terms of collector area and storage tank volume, as well as ideal tilt angle. However, since a detailed model is built in TRNSYS, it is used to compare the performance of various system configurations; the results and the selected system are presented in Chapter 6.

5.8.2. Modeling

Figure 5.15 shows the TRNSYS model used for the solar water heating system. It is to be noted that because the house heating loads have very little impact on the water heating consumption, the performance of the water heating system is modeled separately from the house and its

HVAC systems. The room temperature is set to 20°C and is assumed to be unaffected by the heat losses of the DWH tank.

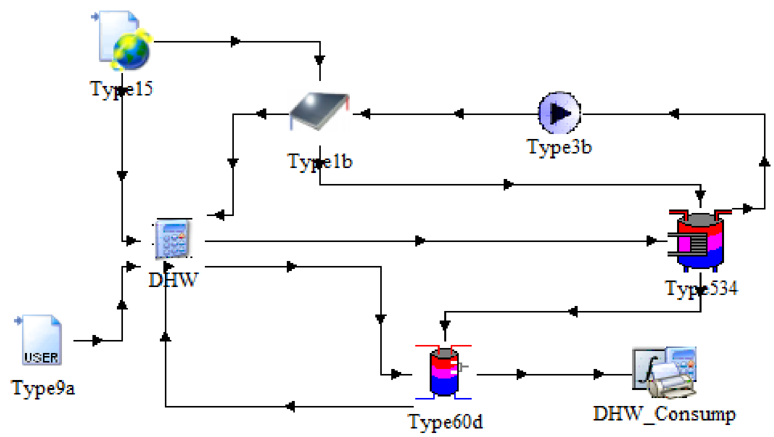

Figure 5.15 – TRNSYS model for the solar water heating system

Type9 provides the same water usage profile as for the standard electrical DHW tank system presented in section 5.5, and Type28 (DHW_Consump) is still used to calculate the yearly energy consumption of the electrical DWH tank, which is significantly lower because incoming water is preheated by the solar collectors. Type15 provides the solar radiation data for the given tilt angle of the solar collector.

Type1 represents a glazed flat plate collector. It is characterized by two equations, according to the Solar Rating Certification Corporation format; Efficiency equation (Equation 5.4) and Incident Angle Modifier equation (Equation 5.5).

$$\varepsilon_c = \eta - \frac{a_1(T_i - T_a)}{G} - \frac{a_2(T_i - T_a)^2}{G} \qquad \text{(Eq. 5.4)}$$

$$IAM = b_1 \cdot S - b_2 \cdot S^2 \qquad \text{(Eq. 5.5)}$$

where ε_c is the efficiency, η is the intercept efficiency, a_1 and a_2 are respectively efficiency equation's slope (in W/m²·K) and curvature (in W/m²·K²) (these three values are given in SRCC data), G is the incident radiation (in W/m²), T_i is the heat transfer fluid inlet temperature, in °C, and T_a is the ambient temperature, in °C. *IAM* is the result of the Incidence Angle Modifier equation, *b1* is the first order IAM coefficient, *b2* is the second order IAM coefficient, *S* is the inverse of the cosine of the incidence angle of the sun on the solar collector, when the incidence angle is between 0° and 60°.

Type1 parameters are outlined in Table 5.14, for the base case system configuration which includes two GOBI 408 collectors.

Table 5.14 – Parameters for Type1 flat plate solar collector

Number of collectors in series	2
Total gross area	5.95 m^2
Fluid specific heat	3.551 kJ/kg·K
Intercept efficiency (η)	0.749
Efficiency slope (a_1)	3.69060 W/m^2·K
Efficiency curvature (a_2)	0.00551 W/m^2·K^2
1st order IAM coefficient (b1)	0.078
2nd order IAM coefficient (b2)	0.086

Type3 is used to model the energy consumption of the pump. The pump used is the model recommended by Heliodyne, a Grundfos UPS 15-58 CiL2. For the flow rates required (from 0.10 L/s to 0.15 L/s depending on the collector area, as specified by Heliodyne), this pump consumes about 50 W. The electricity consumption of the pump is integrated over the full year and added to the electricity consumption of the back-up DHW tank to obtain yearly consumption of the system.

Type534 represents the solar storage tank with an internal coil tube heat exchanger. The model is based on the Bradford White EcoStor SC Solar System tank (Bradford White, 2010). Table 5.15 summarizes the properties of the model, while Figure 5.16 shows its geometry.

Table 5.15 – Parameters for Type534 solar storage tank

Tank volume	283 L (62 imp. gal)
Tank height	1.52 m
Number of tank nodes	4
Edge loss coefficient	0.71 W/m²·K
Coiled tube length	11.02 m
Coiled tube wall conductivity	43 W/m·K
Coiled tube outside diameter	38.1 mm

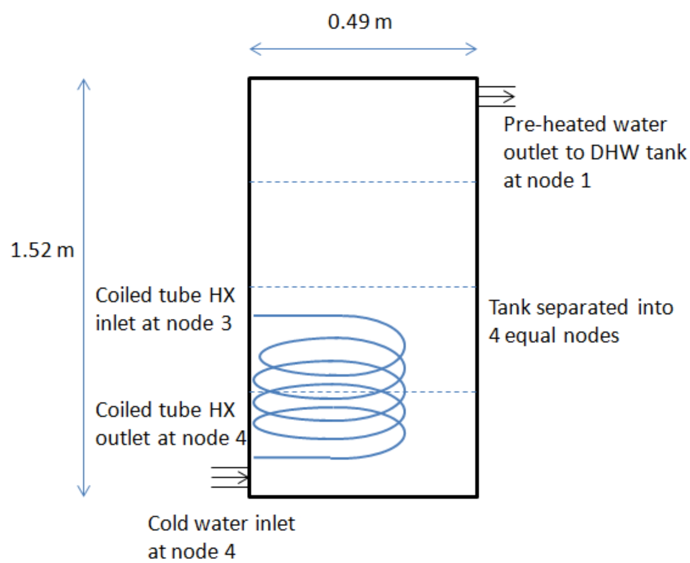

Figure 5.16 – Solar storage tank as modelled

The electrical DWH tank is modelled using Type60 and data from the Giant Factories Super Cascade 9 (61 imp. gal.) tank (Giant Factories, 2011); its properties and geometry are the same as the standard electrical DHW tank described in section 5.7.2.

The system is activated (meaning the propylene glycol solution circulates between the heat exchanger and the solar collectors) when the water temperature at the exit of the solar collectors is at least 6 °C warmer than temperature of node 3 of the solar storage tank (at the level of the internal heat exchanger). The pump is then turned on and the propylene glycol solution flows from the solar collectors to the storage tank.

5.9. Desuperheater and backup electrical DHW tank (for GSHP)

5.9.1. Operation principle

A desuperheater is a heat exchanger that uses extra heat available from the refrigerant vapour at the exit of a heat pump compressor to heat water. It comes as an option on most ground source heat pumps for domestic applications, and on some air source heat pump as well. Because it only recuperates extra heat when the heat pump is on, a desuperheater can only provide part of the annual DHW needs. Figures 5.17 and 5.18 show how the desuperheater works when the heat pump is respectively in cooling or heating mode.

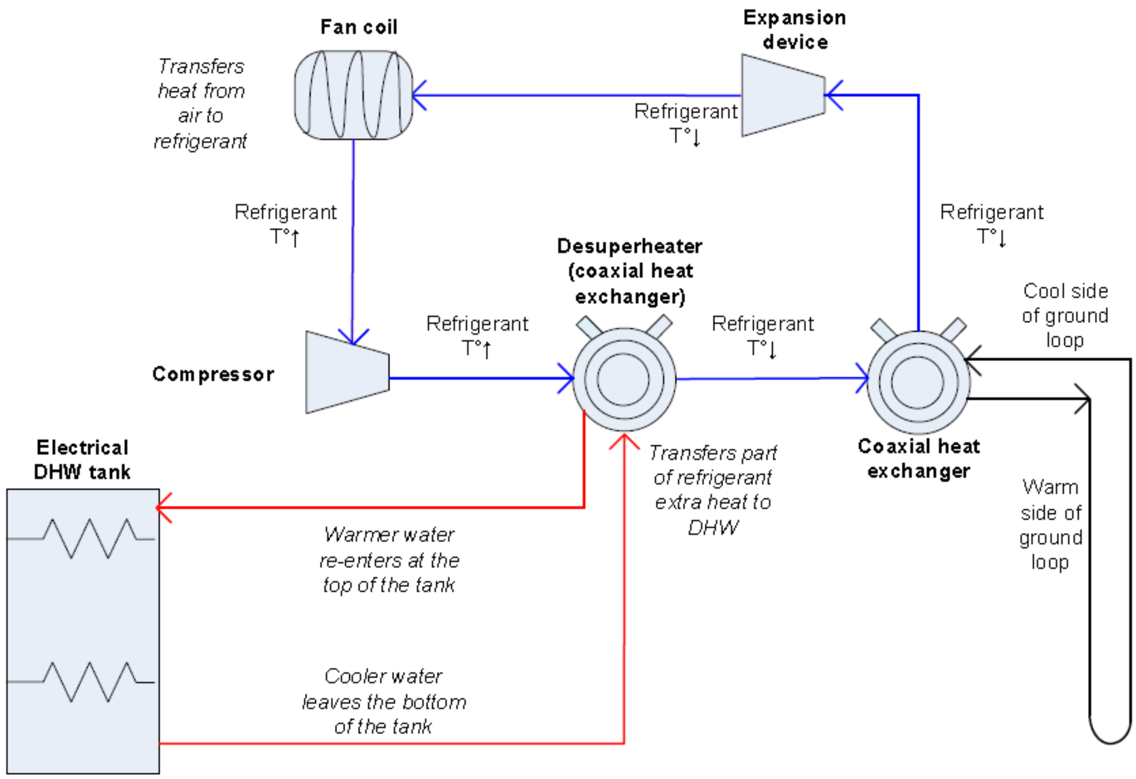

Figure 5.17 – Operation of a heat pump with a desuperheater in cooling mode

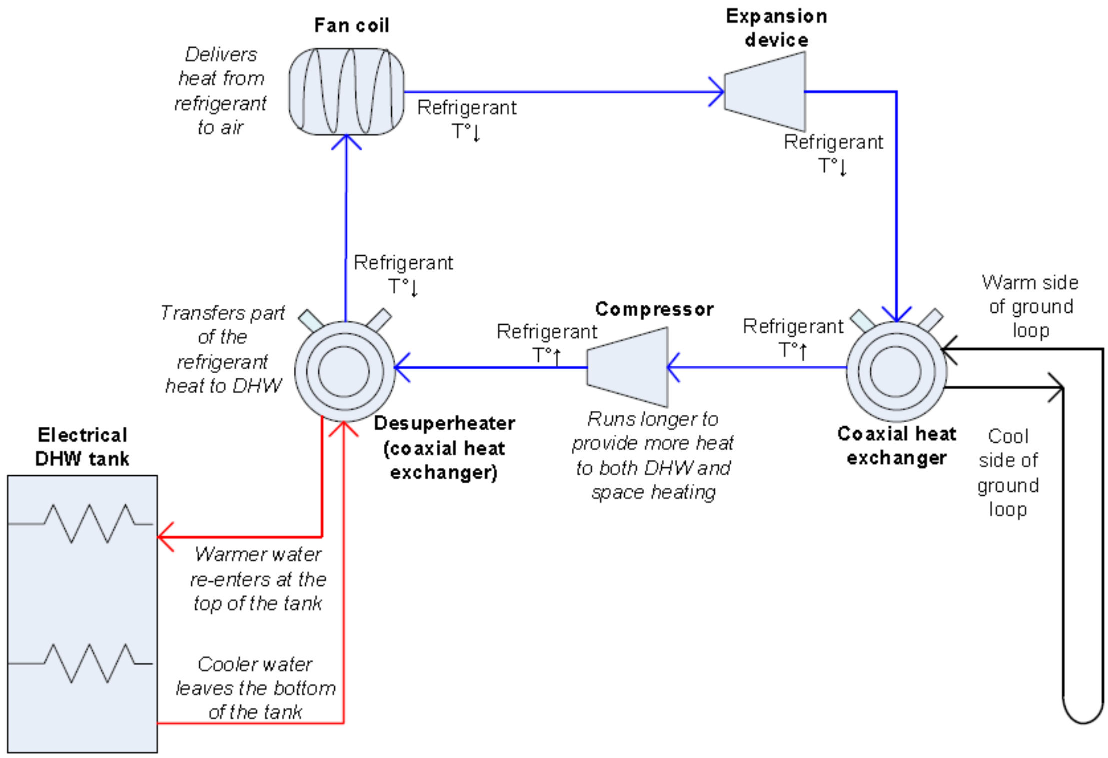

Figure 5.18 – Operation of a heat pump with a desuperheater in heating mode

When the heat pump is in cooling mode, it takes heat from the air (in this case, through the fan coil), compresses the warm refrigerant to increase its temperature and then rejects the heat to a heat sink, which is the outside air for an air source heat pump, and the ground loop fluid for a ground source heat pump. Because the heat needs to be rejected and because it is available at a high temperature at the exit of the compressor, the domestic hot water can then be heated efficiently and for free under these conditions.

When the heat pump is in heating mode, the compressed, high temperature and high pressure refrigerant is used to heat the air. Therefore, removing heat from the refrigerant is not free. However, this heat is provided to the water with the rather high COP of the heat pump, so it makes sense to run the heat pump slightly longer to provide DHW.

5.9.2. Modeling

The modeling of this system is based on a methodology previously described by Picard et al. (2007). Because the DHW heating capacity of the desuperheater is given as a function of the entering ground loop fluid temperature and the status of the heat pump (first or second stage, in heating or cooling mode), it can be decoupled from the whole house simulation. A result file, obtained from the house simulation, contains the status of the heat pump and the temperature of the fluid entering the heat pump for each time step. A model is then developed to simulate the whole system, including the desuperheater, the circulation pump, the electric DHW tank and the DHW usage profile, as can be seen in Figure 5.19.

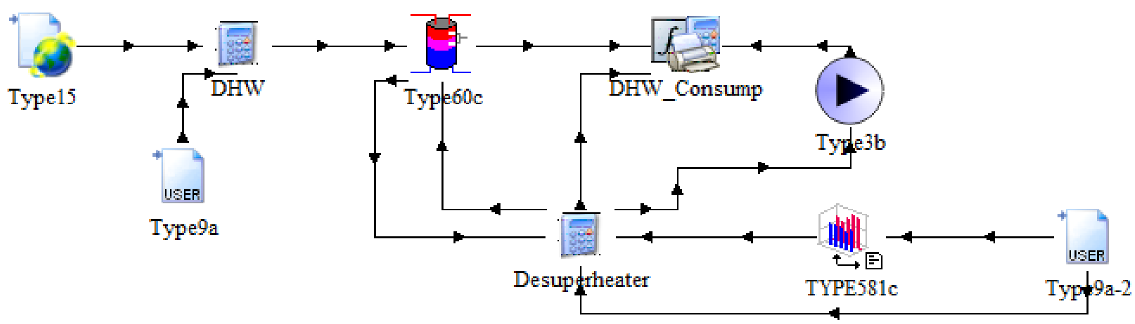

Figure 5.19 – TRNSYS model for desuperheater and electric DHW tank

As for the the solar water heater system and the electrical DHW tank, Type9a reads the DHW usage profile and Type28 (DHW_Consump) calculates the energy consumption for the auxiliary heating of water in the DHW tank.

Type9a-2 reads the results file which includes the heat pump status and the entering fluid temperature for each time step. The heat pump status is represented as follow: 1 or 2 refer to the stage in which the heat pump is operating, and a negative value means that it is in cooling mode. When the heat pump is turned off, its status is set to 0.

Type581c is a multi-dimensional interpolation tool. In this case, it is used to interpolate one dependent variable (the DHW heating capacity) for two independent variables (heat pump status and entering group loop fluid temperature). The table giving DHW heating capacity for the desuperheater, as presented in the technical literature provided by the manufacturer, is available at Appendix C.

The Desuperheater equation block calculates the temperature of the hot water after it passes through the desuperheater, according to equation 5.6.

$$T_{d,out} = T_{d,in} + \frac{DSH_{cap}}{\dot{m}_d \cdot cp_{water}} \qquad \text{(Eq. 5.6)}$$

where $T_{d,in}$ is the temperature of water at the inlet of the desuperheater in °C, DSH_{cap} is the desuperheater water heating capacity in W, $\dot{m}_d$ is the mass flow rate of water through the desuperheater in kg/s and cp_{water} is the specific heat of water (4.19 kJ/kg·K)

Because heating the water through the desuperheater when the heat pump is in heating mode takes heat out of the liquid that would otherwise heat the air inside the house, the heat pump requires to run for a longer time. Therefore, the water is produced not with waste heat that does not affect the electricity consumption of the heat pump, but with the same COP as the heat air. Therefore, the extra electricity consumption to produce that hot water has to be calculated, using Equation 5.7.

$$q_{compDHW} = \frac{DSH_{cap}}{COP_{GSHP}} \cdot gt(Stage, 0) \qquad \text{(Eq. 5.7)}$$

where qcompDHW is the extra electrical input needed by the compressor to heat the water in W, COP_{GSHP} is the coefficient of performance of the ground-source heat pump, and gt(Stage,0) is a Boolean operator that returns 1 when Stage, the heat pump stage, is positive (therefore in heating mode), and 0 when it is negative (in cooling mode). This value in integrated over the year to obtain an electrical consumption in kWh.

Type3b is used to model the energy consumption of the circulation pump. According to Picard et al. (2007), for a 2 ton heat pump, a 50 W circulation pump is required for the desuperheater. The pump is turned on (at full flow) when the heat pump is in function, and its power consumption is integrated by Type28 to obtain the annual electricity consumption.

However, it is to be noted that the results given for the desuperheater are slightly optimistic. The error comes from the entering water temperature, which is assumed to be 32 °C for the desuperheater capacity data given by the manufacturer. Because the desuperheater system presented here does not have a pre-heating tank, the entering water temperature is about 45°C, which means that the efficiency of the heat exchanger will be reduced because of the smaller temperature difference between the cold and the hot sides. As the results already show that, even in an ideal system setting (with a pre-heating tank), the system would not provide significant energy savings, the possibility of either improving the mathematical model or adding a pre-heating tank is excluded.

5.10. Conclusions

In this chapter, TRNSYS 16 was used to model four space conditioning systems (electric resistance, air-source heat pump, cold-climate air-source heat pump and ground-source heat pump) and three domestic hot water systems (electric water heater, flat-plate collectors with electrical back-up and desuperheater with electrical back-up). The design and modeling process put in evidence some issues with the residential HVAC market. Even if there is a certain trend towards smaller and more energy efficient houses, it is still difficult to find small capacity heat pumps in Canada. This leads to over-sizing of equipment, which in turn can cause cycling issues and premature wear of heat pumps. Furthermore, many heat pump manufacturers (mostly for air-source heat pumps) do not provide detailed performance data. This makes it difficult for professionals to accurately assess the energy consumption of each system and choose the best of them, especially when detailed energy simulation is used. Finally, while the models built aimed at being as representative of reality as possible, it was acknowledged that even single-family house HVAC systems and controls can be complex, and some simplifications were applied.

Some preliminary conclusions can be drawn just by observing performance data of each selected piece of equipment. First, it is concluded that the cooling performance of systems will not affect significantly their annual energy performance, because cooling loads are very small for the studied house. Figure 5.20 shows the heating COP for the selected models of ASHP, CCASHP and electric resistance heating as a function of ambient temperature, for an indoor air temperature of 21°C.

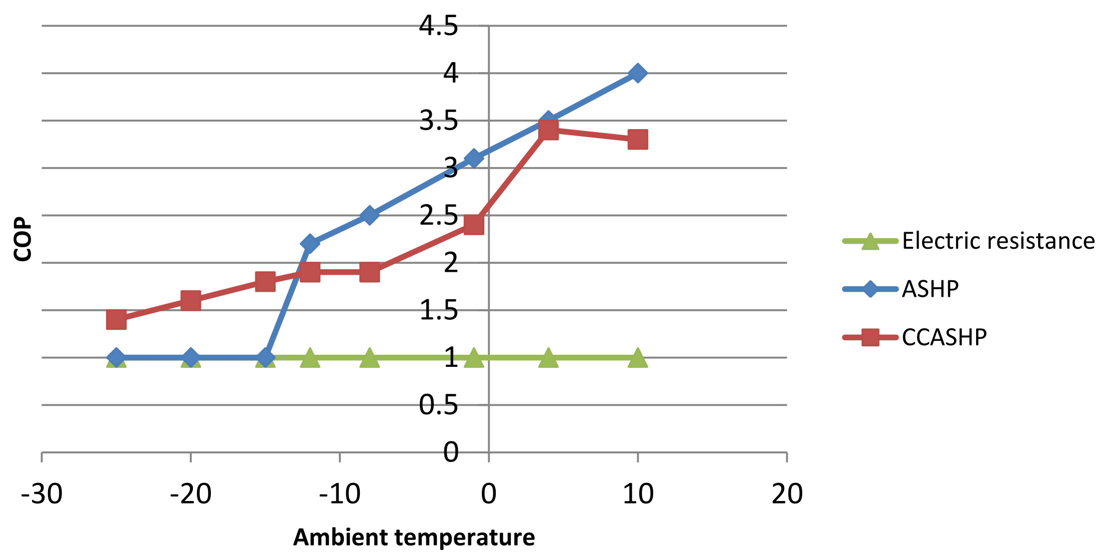

Figure 5.20 – Comparison of heating COP vs ambient temperature for three heating systems

While the CCASHP manufacturer claims that its product will outperform standard ASHP in cold climates because of its higher COP at temperatures below the cut-off point (-12°C), this is not obvious when looking at Figure 5.20. In general, the ASHP has a higher COP than the CCASHP when it is not in resistance mode, and consequently an annual energy consumption analysis is required to compare both heat pumps. Of course, electric resistance heating has the lowest COP of all three systems at all time; however, this is compensated by a very small investment cost and possibly a smaller embodied energy. Ground-source heat pumps efficiency is not directly influenced by ambient temperature and cannot be compared to other systems on the same graph. However, the COP at part load for entering fluid temperature that is at the average annual ground temperature (6.3°C) is approximately 2.4, which is not clearly above neither below typical performances for ASHP or CCASHP. No performance indicators for solar collectors or desuperheater allows for a choice of one of these systems over a standard electric water heater, and therefore further calculations are needed.

The results of energy simulations are presented in Chapter 6, and the LCC and LCE analysis is performed for the comparison of all systems.

6. Life-cycle energy and cost analysis of mechanical systems

In the preceding chapters, optimal solutions for the envelope design as well as computer models for a selection of mechanical systems were presented. Chapter 6 combines both aspects to present simulation results of each mechanical systems coupled to three levels of envelope insulation (code compliant, minimum LCC and minimum LCE). These three envelopes are used to study the interactions between the envelope and the mechanical systems when aiming at minimizing the overall LCC and LCE of the house. Will an envelope that is too insulated to be cost-effective prove to be part of the best combination to minimize cost when coupled to mechanical systems? Or, conversely, should we minimize our investment in the envelope by designing strictly to meet the code requirements, and invest more money in mechanical systems to reduce the operation costs?

The minimum LCC envelope is used as a starting point to analyse the detailed simulation results for each system. Then, the energy consumptions obtained by simulation for all three envelopes are used, in conjunction with data from the literature and the industry, to conduct the energy and cost life cycle analysis and conclude on the best combinations of envelope and mechanical systems from a life cycle perspective.

6.1. Operation performance of mechanical systems for the minimum LCC envelope

The following section compares the energy performance of each system, as modeled in Chapter 5, for the minimum LCC envelope. The overall electricity consumption is used to draw conclusions on the energy savings that can be expected from each system, with respect to their advertised performance. More detailed simulation results for the minimum LCC envelope, as well as the complete LC analysis, can be found at Appendix F.

6.1.1. Simulation results for mechanical systems

Tables 6.1 and 6.2 break down the energy consumption of respectively space conditioning and domestic water heating systems. The results for the solar water heater are those of the lowest LCC system, which is identified based on the analysis given in section 6.1.1. An analysis of these results follow in section

Table 6.1 – Annual energy simulation results for space conditioning systems for the min. LCC envelope

Mechanical system	Heating delivered (kWh)	Cooling delivered (kWh)	Electricity consumed (kWh)	Operation cost ($)
Electric furnace with AC	7,104	688	7,253	568.64
ASHP	6,892	737	4,614	361.74
CCASHP	6,766	841	4,039	316.65
GSHP	6,962	862	2,770	217.17

Table 6.2 – Annual energy simulation results for domestic water heating systems for the min. LCC envelope

Mechanical system	Auxiliary water heating (kWh)	Electricity for pumps & compressor (kWh)	Electricity consumed (kWh)	Operation cost ($)
Electric DHW tank	4,578	0	4,578	358.92
Desuperheater	3,935	266	4,201	329.36
Solar water heater	2,554	82	2,636	206.66

6.1.2. Optimization of the solar water heater with electrical back-up

As explained in Section 5.8.1 of Chapter 5, an evaluation of LCC and LCE was conducted on various configurations of the solar water heater system. The considered variables are outlined in Table 6.3.

Table 6.3 – Design variables for solar domestic hot water heater

Variable	Possible values
Number and size of solar collectors	2 panels of 4’x8’ (size 1), 2 panels of 4’x10’ (size 2), 3 panels of 4’x8’ (size 3)
Tilt angle	30° (roof angle), 40° (with mount)
Storage tank volume	60 U.S. gal, 75 U.S gal.

For each of the 12 possible configurations, the simulation model described in section 5.8.2 was used to obtain operation energy, and LCC and embodied energy was obtained through referenced data. The detailed methodology for life cycle costing and energy calculation is explained in section 6.2. In this case, the operating primary energy consumed excludes solar energy. Figures 6.1 and 6.2 give the results for the LCC and LCE of the solar water heater system.

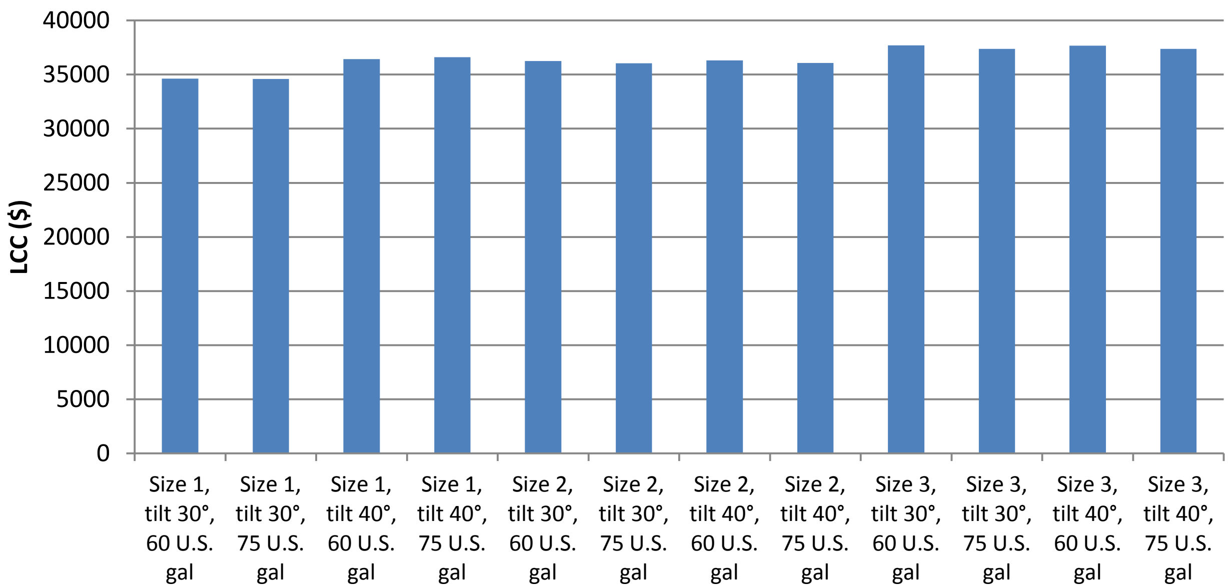

Figure 6.1 – LCC for 12 configurations of solar water heating systems

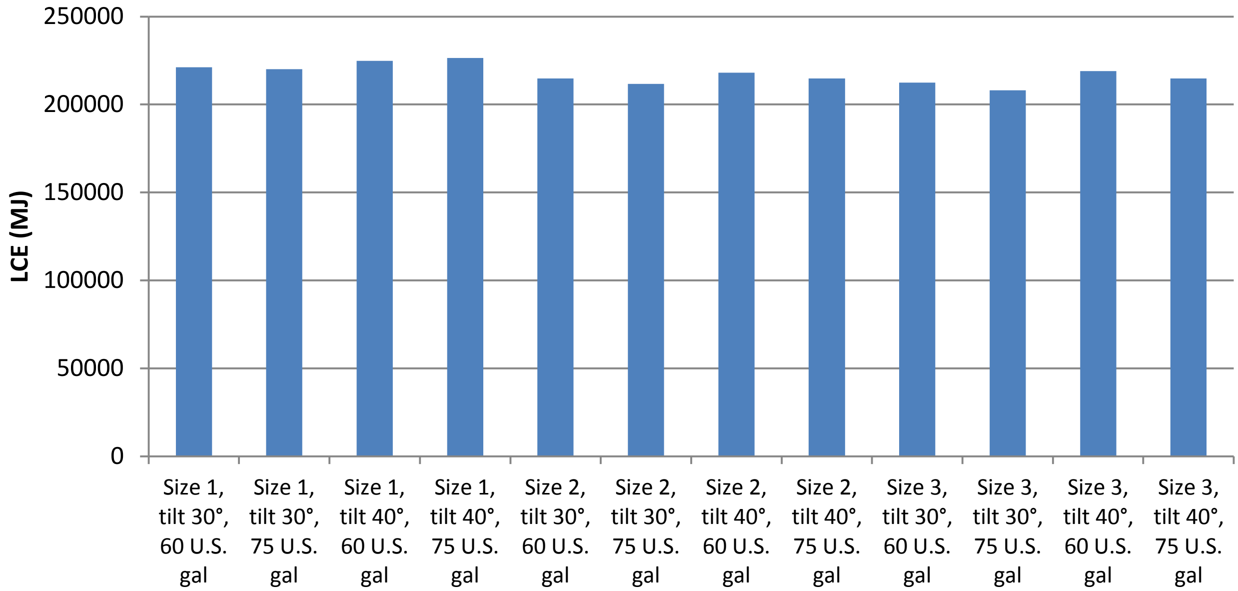

Figure 6.2 – LCE for 12 configurations of solar water heating systems

In this case, because the selected envelope is the one that minimizes LCC, the solar water heating system with a minimum LCC is also selected: 2 panels of 4’ by 8’, with a tilt angle of 30° and a 75 U.S. gal storage tank. The details of the life cycle energy and life cycle cost for this system are part of Appendix E, along with all other mechanical systems for the minimum LCC envelope.

6.1.3. Conclusions on operation of space conditioning system

One interesting metric when comparing the operation performance of space conditioning system is their seasonal COP. For heat pumps, manufacturers give the electricity consumption of their equipment at given indoor and outdoor conditions, but their annual performance depends on specific weather as well as system design. Table 6.4 gives the seasonal heating COP of each space conditioning system for the minimum LCC envelope, based on heating delivered to the air and the electricity consumption (which includes reheating of ventilation air and auxiliary electric element consumption), compared to the COP given in the technical literature (design COP).

Table 6.4 – Coefficient of performance of heating systems for minimum LCC envelope

	Heating delivered (kWh)	Electricity consumption (kWh)	Design COP	Seasonal COP (simulated)
Electrical heating	7104	7104	1.00	1.00
ASHP	6892	4476	2.46	1.54
CCASHP	6766	3862	2.75	1.75
GSHP	6962	2663	5.0	2.61

In technical documentation, the performance of the equipment is usually presented by the heating seasonal performance factor (HSPF); the HSPF corresponds to the seasonal average of the ratio of BTU of heat produced to the watts of electricity consumption. This seasonal average is based on standards weather conditions determined by the Air-conditioning, Heating and Refrigeration Institute (AHRI), which do not necessarily reflect the real conditions of the area where the product will be installed. The column "Design COP" gives the COP equivalent (in watts/watts) of HSPF presented in technical documentation of each piece of equipment, in order to facilitate comparisons. In the case of the GSHP, no HSPF is given, and so the COP for part-load operation is used.

While the performance of the standard air-source heat pumps corresponds to what is usually advertised for this type of equipment, which means a reduction of about 35% of the heating bill over an electric element or gas furnace (Dussault, 2009), the design COP (Johnson Controls, 2011) is misleading when compared to the seasonal COP obtained by simulation. The cold-climate air-source heat pump (Mitsubishi Electric Sales Canada, 2012), which vendors claimed to be in a range of efficiency comparable to ground-source heat pumps, offers only a slight improvement over the ASHP (43% reduction of heating bill) when reheating of ventilation air is considered. In comparison, a GSHP would cut the heating expenses by 62% (but still don't reach a COP of 5.0 as advertised in the technical documentation (Enertech Global, 2011)). It is to be noted that in this case, where the building is highly insulated, that the air-source heat pumps are slightly disadvantaged over ground-source heat pumps. The reason is that a highly insulated building tends to require heating only when it is really cold outside; therefore, the heat pump functions less often when the outside temperature is mild and favorable to a high COP, and this drives the annual COP down.

6.1.4. Conclusions on performance of domestic hot water systems

When looking at the heating loads compared to the DHW loads, it is obvious that the later cannot be neglected. Indeed, while heating systems distribute about 7,000 kWh of heat, 4578 kWh of electricity is required to meet the DWH load. It is therefore important to also consider advanced water heating systems. Because of the small heating loads, the GSHP does not run at a high capacity or for a long period, therefore producing very little extra heat to be used by the desuperheater, which only saves 377 kWh per year. A solar water heater achieves a much higher reduction of the DHW electricity consumption, but its investment cost is rather prohibitive, as it will be seen in sections 6.3 to 6.5.

6.2. Data for life cycle energy and cost of mechanical systems

This section presents the sources and methodology for the LC analysis of mechanical systems and the complete house. Table 6.5 gives the assumptions made for the service life of main mechanical system components. When more than one source is given, an average of the proposed values is taken.

Table 6.5 – Service life of mechanical system components

Mechanical system component	Service life	Source
Air-source heat pump	16 years	National Association of Home Builders (2007)
Central air conditioning unit	15 years	National Association of Home Builders (2007)
Electric DHW tank	11 years	National Association of Home Builders (2007)
Electric baseboards	20 years	National Association of Home Builders (2007)
Flat-plate solar collectors	25 years	Australian Sun Energy. (2010) BRANZ Ltd. (N/A) Good Energy (2012)
Ground-source heat pump	22 years	Rye P. (N/A).
Propylene glycol solution for solar collectors	5 years	Lambert M. (2012)
Solar storage water tank	20 years	Mark Group U.S.A. (2012).

Table 6.6 presents a sample of costs and their source, as well as embodied energy data for mechanical system components. Appendix E gives the details and references for the embodied energy calculations of each component.

Table 6.6 – Cost and embodied energy data for mechanical system components

Mechanical system component	Cost	Source for cost	Embodied energy (MJ)
Air-source heat pump (1.5 tons)	$6,836	Kegel et al. (2012)	7279
Electric furnace +central air conditioning unit (1.5 tons)	$5,924	Duhamel G. (2012)	8276
Electric DHW tank (60 imp. gal)	$791	RS Means (2010) Rona (2012)	2652
Electric baseboards (1000 W)	$158	RS Means (2010)	738
Flat-plate solar collectors (two 4'x8' collectors)	$5,987	Lambert M. (2012)	9758
Ground-source heat pump (2 tons)	$8,544	Survey of contractors in the Montreal area (2012)	7340
Solar storage water tank (60 U.S. gal)	$1,656	Lambert M. (2012)	2757

6.3. LCC and LCE for mechanical systems with the minimum LCC envelope

Some basic assumptions are made for all systems. The life cycle study period is 50 years, to be consistent with the envelope analysis. Each system has a defined service life given in the previous section. If a piece of equipment has to be replaced every X number of years, X not being a factor of 50, the investment cost for its last replacement is multiplied by the ratio of the number of years it will be in use until the end of the 50-year study period to its service life. The same principle is applied to account for embodied energy. As for the envelope, life cycle cost is expressed in terms of net present worth, and is consequently discounted with respect to the year it is incurred. Annual energy costs are given in constant dollars, for year 1. The real discount rate and escalation rate for electricity prices are respectively 0.65% and 2%, as for the envelope analysis (see Section 4.2.2 for further details).

Tables 6.7 and 6.8 summarize the life cycle energy and costs for each of the space conditioning and domestic hot water system for the minimum LCC envelope.

6.3.1. Life cycle performance of systems for heating, cooling and DHW

Table 6.7 – Life cycle performance of mechanical systems for min. LCC envelope

System	Invest. cost ($)	Annual elect. consumption (kWh)	LCC ($)	LCE (kWh)
Electric heating and DHW + central AC (#3)	6,715	11,831	84,454	776,819
Electric heating + central AC + solar water heater (#4)	14,602	9,889	90,162	661,814
ASHP + electric DHW (#5)	7,627	9,194	73,965	604,584
ASHP + solar water heater (#6)	15,514	7,250	79,673	489,579
CCASHP + electric DHW (#7)	6,715	8,617	77,134	571,411
CCASHP + solar water heater (#8)	14,602	6,675	84,842	456,406
GSHP + electric DHW (#9)	13,729	7,348	66,532	484,053
GSHP + desuperheater (#10)	14,413	6,971	65,970	460,494
GSHP + solar water heater (#11)	21,616	5,406	72,240	369,048

6.3.2. Life cycle performance of systems for heating and DHW only

Table 6.8 – Life cycle performance of mechanical systems for min. LCC envelope (no cooling)

System	Invest. cost ($)	Annual elect. consumption (kWh)	LCC ($)	LCE ($)
Electric heating and DHW (#1)	1,877	11,682	71,213	759,505
Electric heating + solar water heater (#2)	9,764	9,740	76,921	644,501
ASHP + electric DHW (#5)	7,627	9,054	73,180	595,622
ASHP + solar water heater (#6)	15,514	7,112	78,898	480,617
CCASHP + electric DHW (#7)	9,905	8,440	76,140	559,933
CCASHP + solar water heater (#8)	17,791	6,498	81,848	444,928
GSHP + electric DHW (#9)	13,729	7,241	65,376	477,122
GSHP + desuperheater (#10)	14,413	6,914	65,649	456,577
GSHP + solar water heater (#11)	21,616	5,299	71,639	362,117

The differences between the heating only and heating and cooling scenarios, as well as the ranking of mechanical systems based on LCC and LCE and the contribution of embodied energy are discussed in Sections 6.6 and 6.7.

6.4. LCC and LCE for mechanical systems with the minimum LCE house envelope

6.4.1. Modifications to the design and simulations of systems

Because the minimum LCE envelope is different from the min LCC one, its heating and cooling loads are different. Table 6.9 gives the energy loads and demands for this house.

Table 6.9 – Energy loads and demands for the minimum LCE envelope

Annual heating load	With night setback	5156 kWh
	Without night setback	5517 kWh
Maximum heating demand	With night setback	7.0 kW
	Without night setback	3.3 kW
Maximum heating demand at -12°C (for ASHP, with night setback)		6.0 kW
Annual cooling load		1026 kWh
Maximum cooling demand		2.1 kW

The sizing of each system is consequently adapted to these loads, and the computer simulations (as described in Chapter 5) reflect these changes. Because the GSHP and ASHP were already at the smallest capacity available on the market, and because the CCASHP is available in only one size, these systems remained unchanged. However, the auxiliary heating element power for the ASHP is modified to meet the maximum demand of 5.5 kW. Electrical baseboards are also downsized to meet this demand. DHW systems remain the same and have the same LCC and LCE as for the minimum LCC envelope case, as water heating demand is unaffected by the envelope. An exception is the desuperheater systems, for which a simulation is conducted once again to take into consideration the use of the GSHP, which changes with this new envelope. Table 6.10 presents the life cycle performance of all space conditioning and DHW systems with the minimum LCE envelope.

6.4.2. Life cycle performance of systems for space conditioning and DHW

Table 6.10 – Life cycle performance of mechanical systems for min. LCE envelope

System	Invest. cost ($)	Annual elect. consumption (kWh)	LCC ($)	LCE (kWh)
Electric heating and DHW + central AC (#3)	6,715	9,790	72,997	644,634
Electric heating + central AC + solar water heater (#4)	14,602	7,848	78,705	529,629
ASHP + electric DHW (#5)	7,627	8,140	68,060	537,052
ASHP + solar water heater (#6)	15,514	6,198	73,768	422,047
CCASHP + electric DHW (#7)	9,905	7,740	72,211	514,597
CCASHP + solar water heater (#8)	17,792	5,798	77,919	399,592
GSHP + electric DHW (#9)	13,453	6,886	63,663	454,658
GSHP + desuperheater (#10)	14,137	6,610	63,667	437,391
GSHP + solar water heater (#11)	21,340	4,944	69,371	339,653

The values presented in this table are discussed in Sections 6.6 and 6.7 to be put in perspective with the corresponding results for the two other house envelopes.

6.5. LCC and LCE for mechanical systems with the code compliant house envelope

Another strategy to reach very low annual energy consumption is to maximize the use of high performance mechanical systems and limit the investment in improving the envelope. In order to evaluate this strategy and compare it to those strategies presented before (minimum LCC and minimum LCE envelopes), a code compliant house was modeled with the same types of mechanical systems as outlined in Chapter 5.

6.5.1. Modifications to the envelope and mechanical systems models

Table 6.11 summarizes the envelope insulation and windows for the minimum code compliant house (exterior and interior finish materials remain the same). The building file in TRNSYS is modified to reflect these changes. The cost is also recalculated, using the same data as for the envelope optimization conducted in Chapter 4; this envelope has a LCC of $199,115. Table 6.12 gives the energy profile for this house.

Table 6.11 – Envelope insulation and windows for minimal code compliant envelope

Exterior walls	Inside insulation: 90 mm fibreglass
	Outside insulation: 51 mm polyisocyanurate
Basement walls	Inside insulation: 51 mm polyisocyanurate
Basement floor	25 mm extruded polystyrene
Roof	Inside insulation: 140 mm mineral fiber
	Outside insulation: 51 mm polyurethane
Windows	Double low-e, argon filled, vinyl frame

Table 6.12 – Energy loads and demands for minimal code compliant envelope

Annual heating load	With night setback	12,050 kWh
	Without night setback	13,000 kWh
Maximum heating demand	With night setback	9.3 kW
	Without night setback	5.6 kW
Maximum heating demand at -12°C (for ASHP, with night setback)		7.0 kW
Annual cooling load		261 kWh
Maximum cooling demand		2.3 kW

The same TRNSYS models are used for each mechanical system, with only a few modifications to parameters. For electric baseboards and central air conditioning, the capacity of baseboards (modelled as convective gains) is increased to meet the loads of each floor: 3.4 kW for the first and second floors, and 2.5 kW for the basement, while the AC unit capacity remains the same because it is already the smallest central AC unit available in this line of product. For the ASHP and the CCASHP, a scaling factor, which is a parameter available in Type665, is used to model a larger capacity without changing the performance table data. As explained in the documentation that comes with Thermal Energy System Specialists (TESS) model 665: "When normalized, many heat pump data files look nearly identical. Consequently it is possible to accurately model a 2 ton heat pump by doubling the heating and cooling power and capacity read from a 1 ton heat pump performance data files."

6.5.1. Life cycle performance of systems for space conditioning and DHW

Table 6.13 – LC performance of mechanical systems with the minimal code compliant envelope

System	Invest. cost ($)	Annual elect. consumption (kWh)	LCC ($)	LCE (kWh)
Electric heating and DHW + central AC (#3)	6,715	16,855	114,410	1,102,198
Electric heating + central AC + solar water heater (#4)	14,602	14,913	120,118	987,193
ASHP + electric DHW (#5)	7,968	11,507	87,919	755,166
ASHP + solar water heater (#6)	15,855	9,565	93,627	640,111
CCASHP + electric DHW (#7)	9,905	10,369	86,968	684,865
CCASHP + solar water heater (#8)	17,792	8,427	92,676	569,860
GSHP + electric DHW (#9)	17,305	8,195	74,863	539,413
GSHP + desuperheater (#10)	17,989	7,603	73,094	501,681
GSHP + solar water heater (#11)	24,192	6,253	80,571	424,408

6.6. LCC comparison of envelope and mechanical systems combinations

The following three figures show the ranking of mechanical systems from the lowest to the highest LCC for each of the three envelopes considered, when both space heating and cooling is provided.

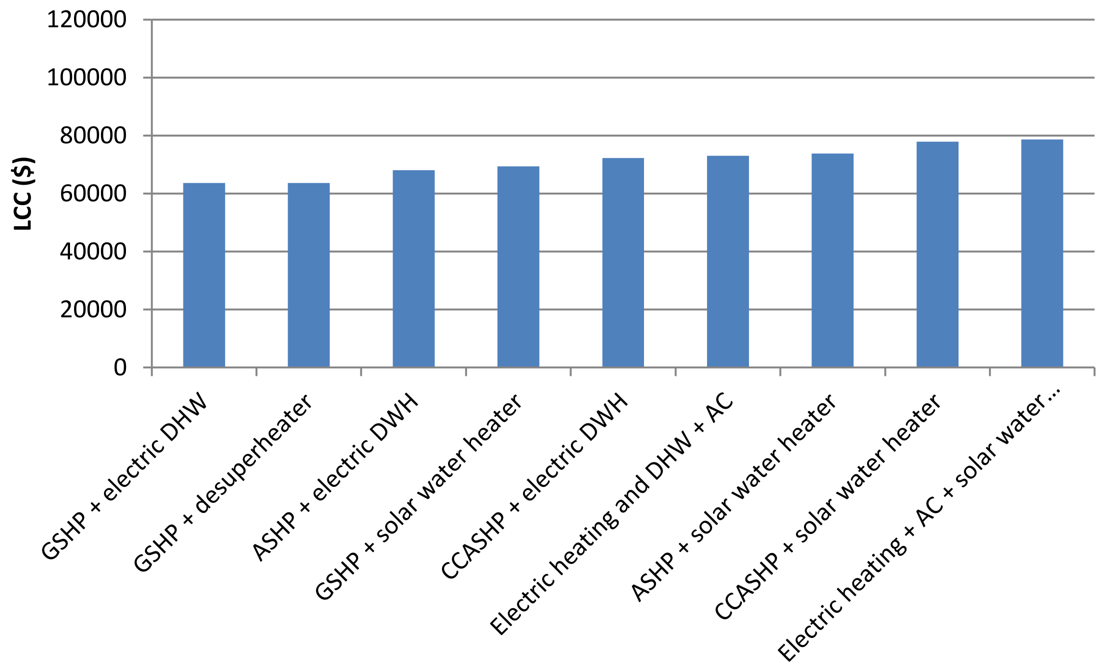

Figure 6.3 – LCC of each mechanical system for the minimum LCE envelope

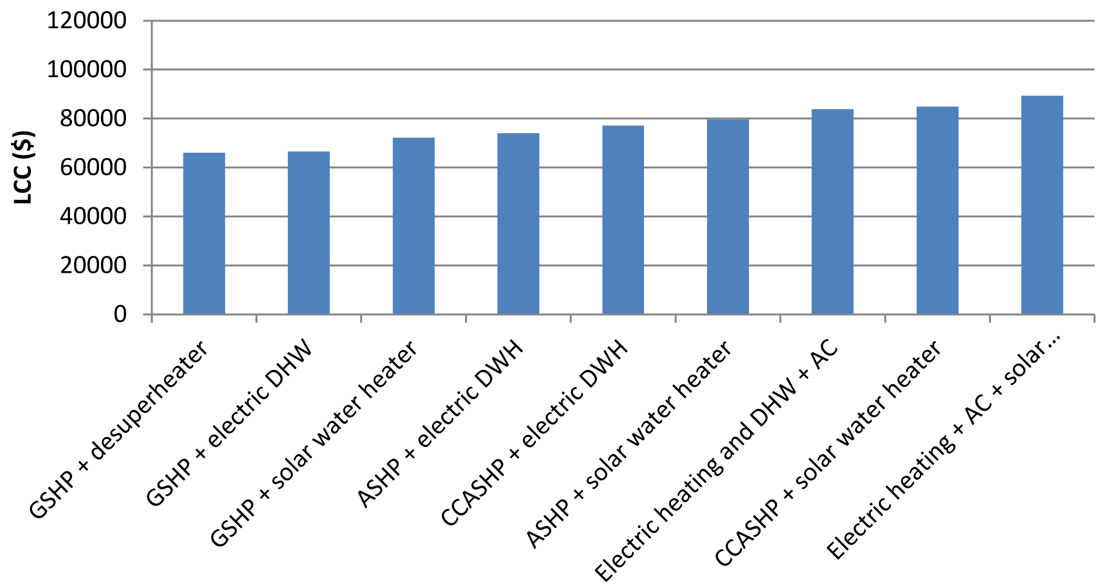

Figure 6.4 – LCC of each mechanical system for the minimum LCC envelope

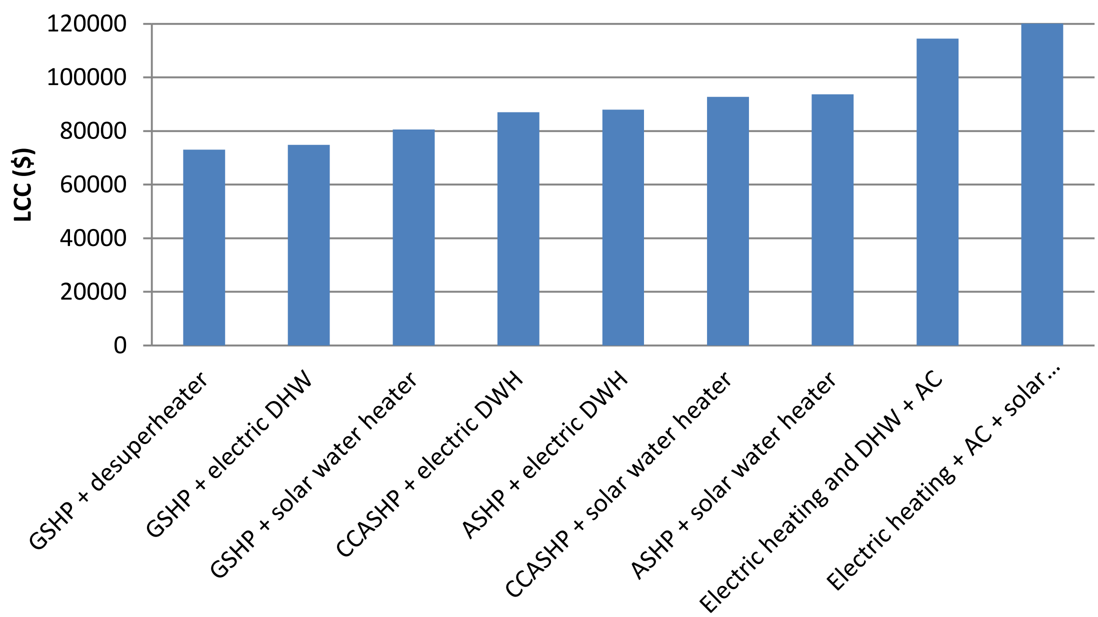

Figure 6.5 – LCC of each mechanical system for the code compliant envelope

It can be observed that in all cases, the GSHP is the lowest LCC space conditioning system, while the rank of CCASHP, ASHP and electrical systems varies depending on the envelope. This contrasts with a common belief that it is not worth investing in a high performance mechanical system if the envelope is very well insulated. Nevertheless, mechanical systems have a larger impact on LCC (and of course LCE) for less insulated buildings; while the LCC difference between the best and the worst system for the minimum LCE envelope is of about $15,000, the difference reaches almost $45,000 for the code compliant house.

The improvement of performance for a CCASHP over a regular ASHP is worth the extra investment cost for the code compliant house, but not for the two better envelopes.

As it was mentioned, the solar water heater is quite effective at reducing the electricity consumption for DWH. However, it because obvious when looking at the life cycle data, that it is not attractive from a LCC perspective. In the case of the minimum LCC envelope, it increases LCC by $5,708 (or 19.7%) over a regular electric DHW tank. The desuperheater coupled to an electric DWH decreases slightly LCC, by $562, but this is a small margin over a 50 years period, and a small error in costs or energy consumption could change that figure. From a LCE point of view however, a solar water heater is an interesting alternative. It decreases the LCE consumption by 38.4%, and the annual electricity consumption by 42.4%. The desuperheater leads to a more modest 7.9% reduction of LCE for DHW production. In conclusion, the DHW systems studied in this thesis are less effective at reducing LCC and LCE than the space conditioning systems.

Table 6.14 looks at the four best combinations of envelope and mechanical system.

Table 6.14 – Lowest LCC combinations of envelope and mechanical system

Envelope	Mechanical system	LCC for envelope and mechanical systems
Code compliant	GSHP + desuperheater	$268,424
Code compliant	GSHP + electric DHW	$270,193
Min. LCC	GSHP + desuperheater	$270,994
Min. LCC	GSHP + electric DHW	$271,556

It can therefore be concluded that the investing in the highest performance mechanical system is a better choice than going beyond code regulations for the envelope. These results are quite consistent with findings by other studies, such as Gustavsson and Joelsson (2010), which showed that heat supply systems had a greater impact on energy consumption than envelope energy-efficiency measures, and Saari et al. (2012), which found that thick insulation was not attractive from an economic perspective. However, they differ from the results of Kegel et al. (2012), who calculated that the LCC of GSHP was only attractive for "net zero energy ready house", and that ASHP was better suited to envelopes with minimal insulation.

The LCC for the four best combinations presented above does not vary significantly; LCC for the best mechanical system for the minimum LCC envelope is within 1% of the overall lowest LCC. However, when choosing the minimum LCE envelope with the associated best mechanical system, LCC reaches $279,100, which is an increase of 4.0%. Furthermore, it has to be taken into consideration that a rather large portion of the LCC is inherent to the existence of the building itself (foundation, structure, minimal amount of windows), and that consequently, small changes in percentage can be more significant than they appear at first sight. Therefore, a minimum LCE envelope is not economically attractive, no matter which mechanical system it is paired with.

6.6.1. Impact of providing only heating on systems ranking

As mentioned previously, the cooling load for a house located in Ste-Agathe-des-Monts is rather small because of the moderate temperatures in this region during summer. Air conditioning therefore might be regarded as unnecessary, which would modify the design of HVAC systems. Figure 6.6 presents the ranking of heating and DHW systems for the minimum LCC envelope without AC.

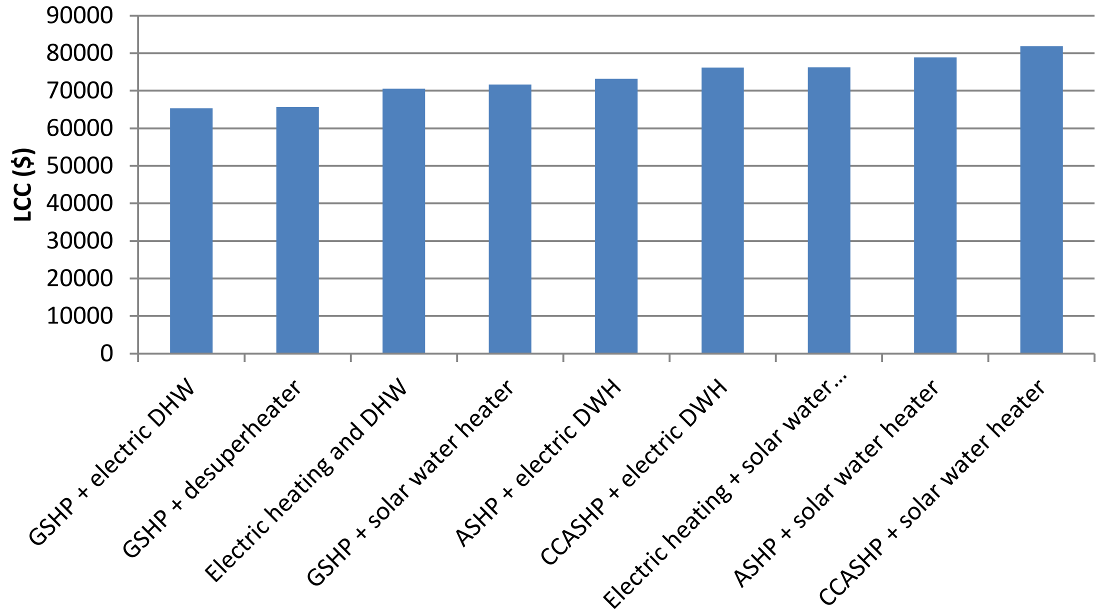

Figure 6.6 – LCC of each mechanical system for the min LCC envelope, without air conditioning

The most notable change in the ranking of system is that electric heating and DHW is now the third best system for LCC instead of the 7th. The reason for that is that the central furnace with AC can be replaced by simple electric resistance baseboards, consequently reducing the investment cost for HVAC system. However, the GSHP still has the lowest LCC of all heating systems.

It can also be noted, from this graph as well as from detailed results in Sections 6.2 to 6.4, that adding air conditioning has only a limited impact on LCE and LCC of the best system. Because GSHP is already the lowest LCC and LCE system, adding air conditioning increases the mechanical system LCC in the minimum LCC envelope by $321 (0.5%), while the LCE rises by 3917 kWh (0.9%). Of course, this impact is more significant if an electric baseboards system is changed for a central electric furnace with air conditioning. Then the increase in LCC would be of $13,587 (13.5%), and of 12257 kWh (1.1%) for LCE.

6.6.2. Making the best design decision based on investment cost

In an ideal world, every future home-owner would buy a house based on long-term environmental and cost considerations. However, investment cost is often what matters most, and this prevails over potential savings in future years. Therefore, incremental investment cost for different envelopes and mechanical systems over a minimal code compliant house with electric heating, cooling and DHW is presented in Table 6.15.

Table 6.15 – Comparison of investment costs and LCC for different energy efficiency measures

Envelope	Mechanical system	Incremental investment cost ($)	LCC reduction ($)	LCC reduction/ Incremental invest cost
Code compliant	Electric heating, AC and DHW	0	0	0
Code compliant	ASHP and electric DHW	1,253	26,491	21.1
Code compliant	CCASHP and electric DHW	3,247	27,442	8.5
Code compliant	GSHP and desuperheater	11,304	41,316	3.7
Min. LCC	Electric heating, AC and DHW	15,566	20,874	1.3
Min. LCE	Electric heating, AC and DHW	34,912	6,501	0.2

It can be concluded from inspection of this table that mechanical systems have a much more interesting ratio of LCC reduction to incremental investment cost than envelope improvement measures. This can be explained by the fact that thermal resistance for homes have been increased recently in building regulations. Indeed, in 2012, some major modifications to the building code were put in application, therefore replacing old regulations dating back to 1992. Those modifications include mandatory insulation of the basement floor, and a much higher insulation for the roof (from RSI 5.6 to RSI 7.2). In the case of this detached house, the new requirements translate to an annual heating load of 12,050 kWh instead of 24,670 kWh. This significant envelope improvement leaves little room to further cost effective energy efficiency measures, and this partly explain the much better return on investment for mechanical systems.

However, the picture might be different if central air conditioning is not included, therefore significantly increasing the incremental investment cost for mechanical systems, and the corresponding LCC reduction. Table 6.16 presents this possibility and its impact on costs.

Table 6.16 – Comparison of investment costs and LCC for different energy efficiency measures

Envelope	Mechanical system	Incremental investment cost ($)	LCC reduction ($)	LCC reduction / Incremental invest cost
Code compliant	Electric baseboards and DHW	0	0	0
Code compliant	ASHP and electric DHW	5,558	13,600	2.4
Code compliant	CCASHP and electric DHW	7,552	14,955	2.0
Code compliant	GSHP and desuperheater	15,609	28,094	1.8
Min. LCC	Electric baseboards and DHW	15,566	14,740	0.9
Min. LCE	Electric baseboards and DHW	34,912	6,111	0.2

One thing that remains constant is that mechanical systems require smaller investment costs, and lead to a better LCC reduction to investment cost ratio. Nevertheless, for an ASHP, an incremental cost of $5,558 for a LCC saving of $13,600 will be much more difficult to sell to customers than a $1,253 incremental cost for a LCC saving of $26,461, as it was the case for the heating and cooling mechanical systems. The lowest LCC option, the code compliant envelope with a GSHP and a desuperheater, requires a similar investment as a minimum LCC envelope, but yields a LCC reduction that is twice as high.

6.6.3. Sensitivity of LCC ranking to discount rate

The choice of the discount rate has been discussed previously in Chapter 4, but it is interesting to see how the ranking of mechanical systems would be affected if a different discount rate was selected. LCC for each mechanical system for the code compliant envelope is recalculated for three other discount rates, the results are illustrated in Figures 6.7 and 6.8. No lower discount rate than the one previously used (2.69%) is considered, because it would then be less than inflation, making investment unattractive. For clarity, the results are presented on two graphs, as the scale of LCC changes as discount rate increases.

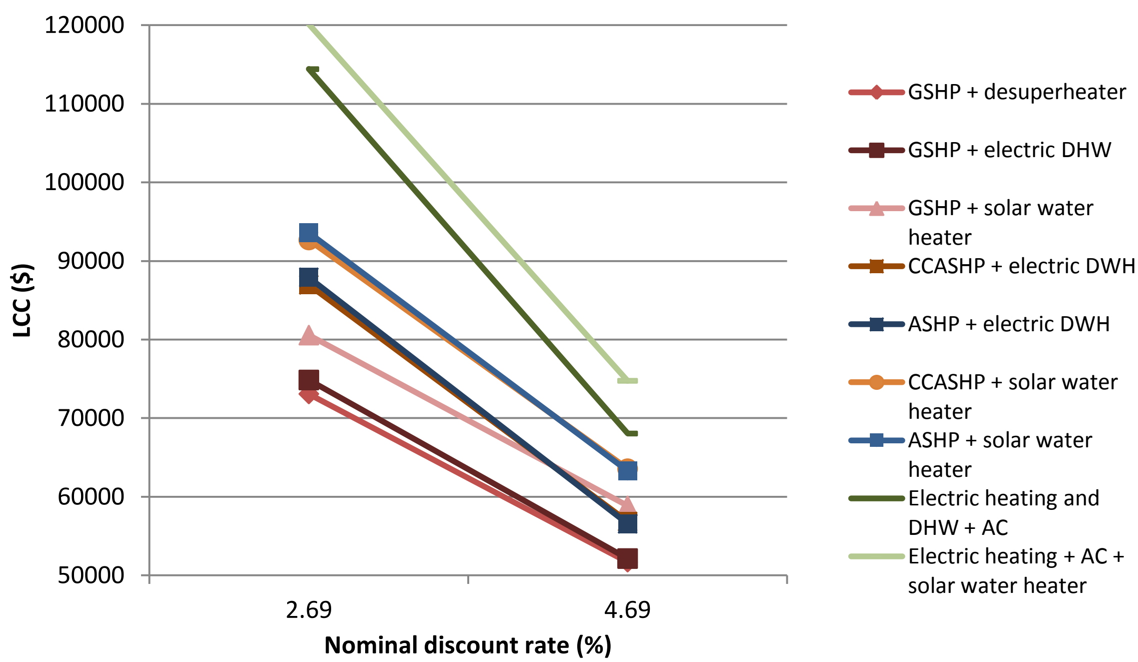

Figure 6.7 – Variation of LCC mechanical systems vs. discount rate for the min. LCC envelope (1)

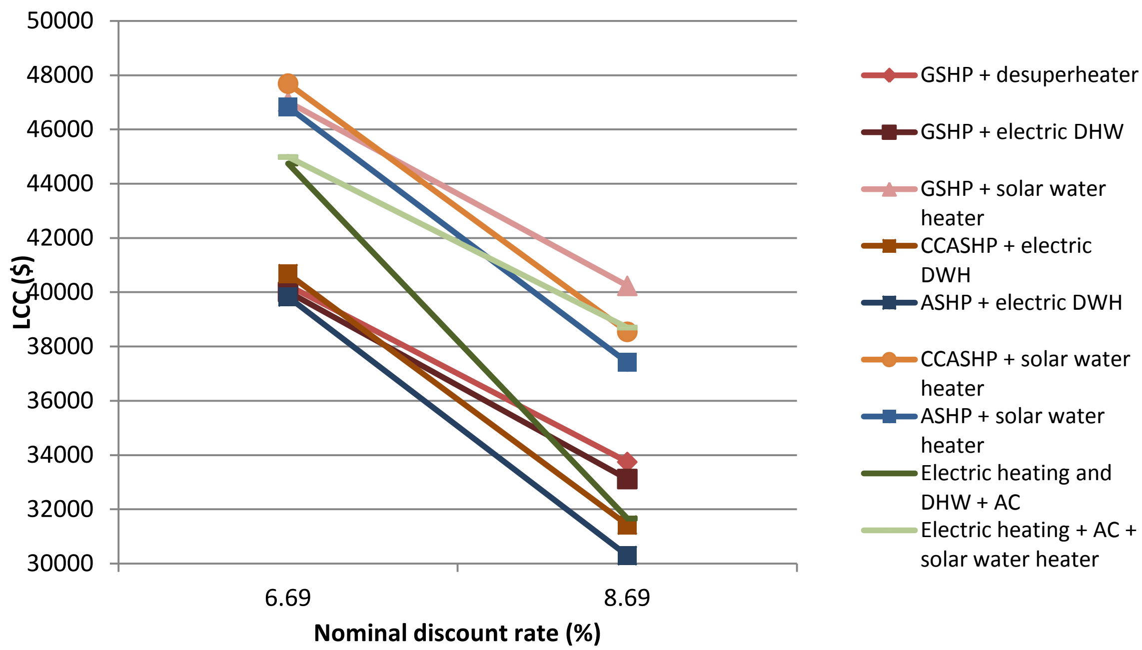

Figure 6.8 – Variation of LCC mechanical systems vs. discount rate for the min. LCC envelope (2)

For an increase of two points of percentage of the nominal discount rate, most systems keep their rank in terms of LCC. Mostly solar water heating systems, which were already unattractive at a nominal discount rate of 2.69%, are losing ranks because they are less and less profitable as discount rate increases. Consequently, it can be concluded that the ranking of mechanical systems in terms of LCC is not particularly sensitive to discount rate. At a rate of 6.69%, ASHP with electric DHW has a lower LCC than GSHP, and becomes the best alternative, while CCASHP becomes a better alternative than GSHP at a nominal discount rate of 8.69%. It is also to be noted that the fully electric heating and DHW system, which is the most widely used in the province of Quebec at this time, never makes it as the best system, even with a discount rate as high as 8.69%.

6.7. LCE analysis for the three envelopes and their mechanical systems

The decision was made to include embodied energy for mechanical systems as well as envelope, based on previous studies. It is interesting to look at the contribution of mechanical systems on embodied energy and the impact of embodied energy on the LCE ranking of mechanical systems.

6.7.1. Impact of embodied energy on LCE

Figures 6.9 and 6.10 show the LCE distribution between embodied energy (EE) and operation energy (OE) for both the code compliant and the minimum LCC envelopes, with the same electrical heating, AC and DHW system. Total LCE is estimated at 1,227,772 kWh for the code compliant envelope with all electric mechanical systems; the embodied energy of envelope and mechanical systems account for 10.7%.

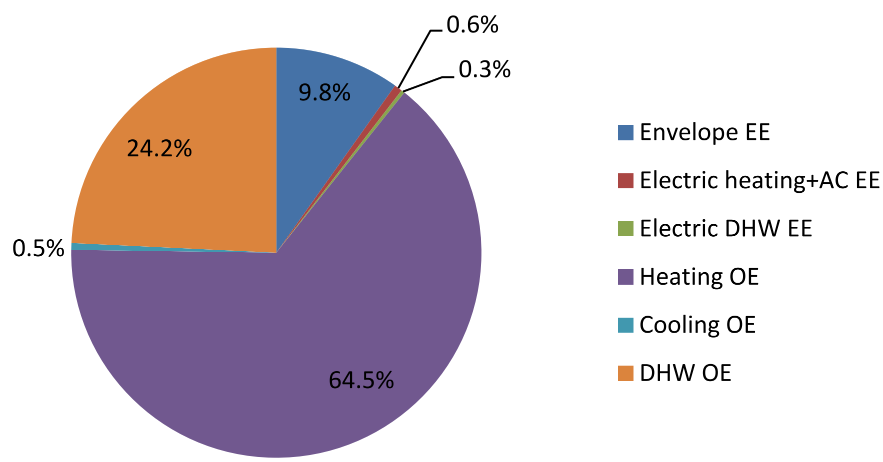

Figure 6.9 – Distribution of LCE for CC envelope with electrical heating, AC and DHW

Total LCE is estimated at 891,682 kWh for the minimum LCC envelope with all electric mechanical systems; the embodied energy of envelope and mechanical systems account for 14.1%.

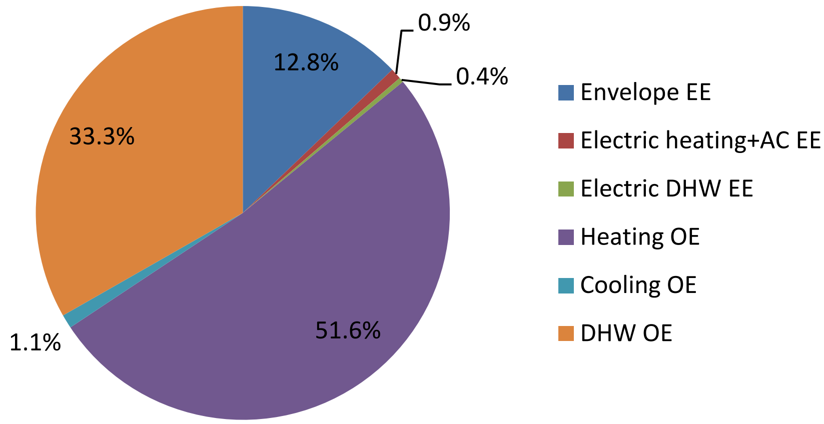

Figure 6.10 – Distribution of LCE for min LCC envelope with electrical heating, AC and DHW

While DHW operation energy represents a larger portion of LCE for the minimum LCC envelope because heating loads are reduced by the improved insulation, the proportion of embodied energy is rather steady for both envelopes. Also, in both cases, the share of embodied energy of mechanical systems is about 1% of LCE, and is therefore rather insignificant. However, Figure 6.11 shows a very different distribution of LCE for the minimum LCE envelope with a GSHP and solar water heater, where the total LCE is of 470,356 kWh.

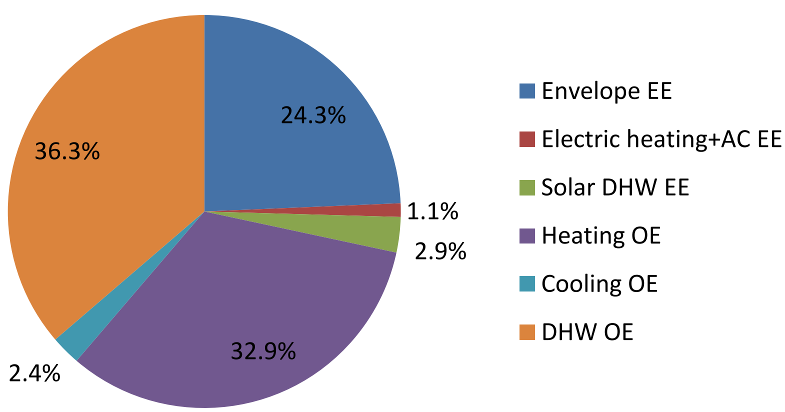

Figure 6.11 – Distribution of LCE for min LCC envelope with GSHP and solar water heater

For this case, embodied energy due to mechanical systems is more significant: approximately 4% of total LCE. Furthermore, total embodied energy represents more than a quarter of LCE. The distribution of operating energy is also different; operating energy for DHW is higher than for heating, due to the very high coefficient of performance of the heating system. However, even though embodied energy of mechanical systems can reach about 5% of LCE for a house, the embodied energy does not have an impact on the selection of a system based on its LCE. Figure 6.12 gives the life cycle energy as a function of annual operating energy for all nine possible mechanical systems for the minimum LCC envelope. It is to be noted that in this case LCE excludes embodied energy from the envelope.

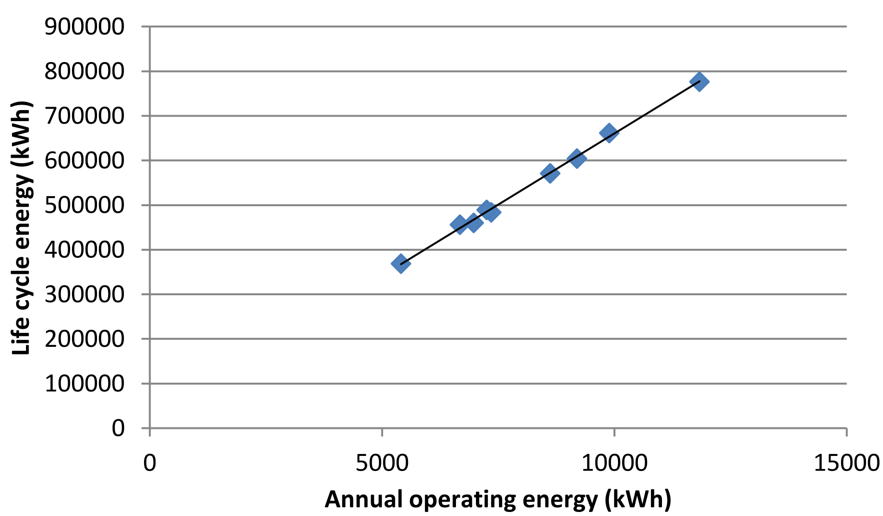

Figure 6.12 – LCE as a function of annual OE for mechanical systems for the min. LCC envelope

Given the correlation coefficient of 0.9978, it is deducted that LCE is highly proportional to operating energy, and that, consequently, embodied energy does not vary enough amongst mechanical systems considered here to make a difference in their LCE.

6.8. Conclusions

In this chapter, mechanical systems were simulated and their life cycle energy and cost were analyzed for three levels of envelope insulation. It was found that a minimal code compliant envelope with the highest performing heating and cooling system, the ground-source heat pump, and a desuperheater with electrical backup, has the lowest LCC of all alternatives. Furthermore, mechanical systems were shown to diminish LCC by a larger amount for smaller investment costs than improvements to the envelope. GSHP proved to be cost effective for all envelopes, and this result is not very sensitive to an increase of discount rate. For water heating, a desuperheater is cost effective for the code compliant and the minimum LCC envelopes, but a standard electric DHW tank is preferred for the minimum LCE envelope.

Repartition of LCE between embodied and operating energy does not vary much depending on the envelope that is selected. However, mechanical systems have a bigger impact on this repartition, and when a high performance equipment is selected, the total house embodied energy can make up more than a quarter of total LCE. The embodied energy was found not vary much for the different mechanical systems studied, and therefore does not impact the selection of the minimum LCE system. Consequently, from a LCE perspective, the system with the smallest operation energy is the one to be selected; in this case, a GSHP with a solar water heater.

7. Conclusions

In this thesis, a detailed base case model of the envelope was first developed with TRNSYS 16 to take into account solar radiation, ventilation and heat recovery, heat transfer to the ground, thermal bridging and HVAC controls, amongst other parameters. The life cycle cost and energy of the initial design was used as a comparison point for optimal designs found later.

An optimization model was then developed to consider several design variables, such as different framing structures and the insulation materials for each type of walls, area of south fenestration and use of concrete floors as thermal mass. The model included equations that calculated embodied energy as well as life cycle cost for the envelope materials and construction. For that purpose a database for energy and cost was built, using tools like the Athena Impact Estimator as well as other sources from scientific literature for energy, and RS Means as well as surveys of local contractors for cost. The complete model was then coupled to GenOpt, a general optimization program, which ran a Particle Swarm optimization algorithm to find optimums in terms of LCC and LCE.

Four space conditioning and three domestic hot water systems were then sized and modeled in TRNSYS for the minimum LCC and minimum LCE envelopes, as well as a minimal code compliant envelope. Their embodied energy and investment cost were evaluated, and the results of the simulations allowed an evaluation of their energy performance. The total LCC and LCE of each alternative was finally compared to find optimal combinations of envelopes and mechanical systems. The following conclusions were drawn:

1. The initial design, which was thought to be an energy efficient building, was in fact very far from optimal both in terms of LCC and LCE.

2. Fibreglass and mineral fibre were found to be the most cost-effective materials for cavity insulation, while polyisocyanurate outperforms other materials for outside insulation.
3. Both the minimum LCC and LCE envelopes have a very thick layer of outside stud insulation, which proves the importance of reducing thermal bridging in energy efficient envelopes. Another similarity between the two envelopes is the use of concrete floors for thermal mass, which is both cost and energy effective.
4. The detailed simulation of a cold-climate air-source heat pump showed that its annual performance is better than a standard ASHP for the specific climate of Quebec, but still not close to the performance of GSHP.
5. Ground-source heat pump is the best space conditioning system from a LCC and LCE perspective no matter which of the optimal or code compliant envelopes is selected. Therefore, the environmental criterion does not always go against the economical criterion.
6. All mechanical systems' additional embodied energy (over an electric system) pays back in energy savings. It was also found that their embodied energy does not vary significantly enough so that it impacts their ranking; consequently, the lowest LCE system is always the one with the lowest annual operating energy consumption.
7. A GSHP is a more cost effective investment than the best investment in envelope improvement. In general, mechanical systems yield a larger diminution of LCC for a smaller investment cost than envelope improvements.
8. For electric heating, which is the most widely used system in Quebec, to be close to the best systems in terms of LCC, discount rate had to be as high as 8%. GSHP stayed

amongst the lowest LCC systems up until that point, which means that this result is not very sensitive to economical assumptions.

7.1. Contributions

1. Review of the state of life cycle analysis in the design of low-energy houses in cold climates
2. Life cycle optimization for the design of a single-family house envelope for southern Québec, using life cycle energy and life cycle cost as objective functions
3. Analysis of trends in design parameters of the studied envelope for minimizing life cycle energy and cost
4. Development of detailed simulation models for assessing the annual performance of four space conditioning systems and three domestic hot water systems in a cold climate, as well as their life cycle cost and energy consumption
5. Optimization of the LCC for a solar domestic hot water system, considering the collector area, inclination angle and storage tank volume
6. Comparison of a super-insulated envelope versus high-performance mechanical system design strategy for a low-energy house from a life cycle cost and life cycle energy point of view
7. Analysis of the relative impact of mechanical systems and envelope embodied energy to the life cycle energy consumption of a single-family house

7.2. Limitations and future work

First of all, there are some parameters of this study that limit its applicability. It is to be specified that the conclusions on the life cycle optimization of the envelope apply to the house geometry that was selected, for the given selected optimization parameters. Other studies would be required to see which conclusions could be generalized to houses in Québec.

Additionally, control strategies implemented in the simulation models were simplistic, because of the numerous mechanical systems considered and the amount of work that a more comprehensive approach would have required. A future study should consider other control strategies, which could have a significant impact on the performance of some of the mechanical systems.

While the LCC and LCE analysis that has been conducted in this study gives a good indication of the performance of envelope energy efficiency measures and advanced mechanical systems, a complete life cycle assessment would draw a more complete picture of the environmental impacts of each choice. Moreover, the electricity mix in Quebec, which is dominated by hydroelectricity, is peculiar and the results could be very different from other studies conducted, mainly in the United States and in Europe. However, this work would need to overcome another challenge that has been identified in the course of this thesis: the lack of reliable and applicable life cycle data for Canada. For embodied energy of mechanical systems, the author used values that came mostly from United Kingdom and New Zealand, because no better freely available databases could be found in the scientific literature. As LCA becomes a more popular practice both in research and in the industry, it is expected that more applicable data will become available in Canada.

The quality of data for cost and service life is also a concern. Very few reliable sources exist to estimate the durability of components such as heat pumps or solar panels. Furthermore, cost can vary significantly depending on distributors and technologies. New mechanical systems are often not listed in cost databases such as RS Means. Further data collection in this area would be beneficial, as well as sensitivity analyses to evaluate the impact of errors.

Another avenue that could be taken is to consider other mechanical systems. Some suggest that air solar thermal collectors or that solar combisystems could be profitable in cold climates. In the next few years, as the price of photovoltaic panels decrease, they might become a good way to reduce the overall energy consumption of a house. Indeed, changing technologies and economic conditions will call for a re-evaluation of this work periodically.

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9. Appendix A: Advanced houses in Canada

Project	**Inspiration by Minto**	**Alstonvale**	**Ecoterra**	**Abondance le Soleil**	**Riverdale**
Location	Ottawa, ON	Hudson, QC	Eastman, QC	Montréal, QC	Edmonton, AB
Project	EQuilibrium	EQuilibrium	EQuilibrium	EQuilibrium	EQuilibrium
Heated area (m^2)	218.5	230	234	238 (3 units)	350 (2 units)
Thermal resistance (m^2.K/W)					
Above ground walls	7.75	5.6	6.69	7.04	9.86
Roof	10.56	12	6.34	12.32	17.6
Foundation walls	6.69	-	2.6	6.34	9.51
Foundation floor	2.64	4.6	1.3	2.64	4.22
Envelope components					
Thermal mass	Double water tank (454 L each)	20 cm and 6.5 cm concrete floors, masonery wall and 4500-L tank	Concrete ventilated slab in basement	-	17 000 L seasonal thermal storage water tank, 20 000 kg of thermal mass inside the house
Airtightness ($ACH_{50\ Pa}$)	0.65	0.3	0.88	0.4	0.5
Window type	Triple argon-filled with low-e	Triple argon-filled with low-e	Triple argon-filled with low-e	Triple-glazed	Triple and quadruple argon-filled with low-e
Wall framing	Double-stud	n/a	2 per 6	n/a	Double stud, 400 mm thick
Mechanical systems					
Heat supply	Forced-air with fan-coil	Hydronic radiant floors	Forced-air with fan-coil	Forced-air with fan-coil	Forced-air with fan-coil
GSHP	-	Yes, connected to the heat pumps	Yes	10.6 kW GSHP per unit	-
Photovoltaic panels	6.2 kW	8.4 kW, BIPV-T	3 kW, BIPV-T	13.8 kW	5.6 kW for each unit
Solar thermal collectors	Water (3 m^2)	40 evacuated tubes water collector	-	17.3 m^2	22 m^2 vertical solar water heater per unit
Heat pump	-	2 heat pumps (geothermal and from BIPV-T)	-	-	-
Other energy source	Gas boiler	Electrical backup	-	5 kW backup electrical coil	12 kW backup electrical heating element
Mechanical ventilation	HRV, 33 or 65 L/s	n/a	HRV, 50 L/s	HRV, 28 L/s per unit	HRV, 48.2 L/s
Solar radiation control	-	Motorized theather curtain and overhangs	Overhangs	Green wall	Overhangs over south windows

Project	**Avalon Discovery 3**	**Now House Retrofit**	**Laebon CHESS Project**	**Urban Ecology**
Location	Red Deer, AB	Toronto, ON	Red Deer, AB	Winnipeg, MN
Project	EQuilibrium	EQuilibrium	EQuilibrium	EQuilibrium
Heated area (m^2)	240.4	139	229	119.5
Thermal resistance (m^2.K/W)				
Above ground walls	12.29	7.22	9.2	11.44
Roof	15.3	6.34	14.1	14.08
Foundation walls	-	4.40/4.93	9.5	n/a
Foundation floor	10.6	4.40	3.5	n/a
Envelope components				
Thermal mass	Slab-on grade (concrete floor) and 2 450-L water tanks	Concrete slab in the basement	2 1,454-L water tanks	n/a
Airtightness ($ACH_{50\ Pa}$)	0.5	1.5	0.5	0.75
Window type	Triple-glazed and insulated shutters	Double-glazed	Quadruple-glazed	Triple and quadruple-glazed
Wall framing	Double SIPs	Original wood frame from the 60's	SIPs	n/a
Mechanical systems				
Heat supply	Hydronic radiant floors	Hydronic radiant floors and forced-air with fan-coil	Hydronic radiant floors	Hydronic radiant floors
GSHP	-	-	10.6 kW	-
Photovoltaic panels	8.3 kW	2.7 kW	6.73 kW	0.5 kW
Solar thermal collectors	6 30-tube flat panel water solar collector	Water solar thermal collector	10 solar thermal panels (water)	4 panel flat plate thermal solar collectors
Heat pump	-	-	-	Air source HP using basement air
Other energy source	Electric boiler back-up	Tankless gas boiler	Electric back-up for DHW	Back-up inline electric heater
Mechanical ventilation	HRV, 60 L/s	HRV, 55 L/s	HRV, flow rate n/a	2 HRV in series, flow rate n/a
Solar radiation control	Overhangs	Retractable awnings	-	-

Project	**Green Dream Home**	**Harmony House**	**Écohabitation**	**BL Écoconstruction**	**Rideau Residence**
Location	Kamloops, BC	Burnaby, BC	Montréal, QC	Ste-Martine, QC	Ottawa, ON
Project	EQuilibrium	EQuilibrium	LEED Platine	LEED Platine	LEED Platine and Passivhaus
Heated area (m²)	284	438 (2 units)	n/a (2 units)	n/a	274 (2 units)
Thermal resistance (m².K/W)					
Above ground walls	10.57	7.04	5.28	7.04	7.57
Roof	7.75	10.56	8.80	10.56	n/a
Foundation walls	7.75	7.92	n/a	3.96	n/a
Foundation floor	3.52	3.52	n/a	3.96	1.76
Envelope components					
Thermal mass	Some concrete floors	-	-	Concrete floors	Concrete floors
Airtightness ($ACH_{50\ Pa}$)	0.68	n/a	n/a	n/a	< 0.6
Window type	Triple-glazed, 0.75-0.85 m².K/W	Triple-glazed, argon-filled, low-e 1.06 m².K/W	Energy Star	n/a	Triple-glazed
Wall framing	ICFs	2x6 studs with vacuum insulation panels	-	Double studs (2x4 and 2x3)	2x6 with heavy exterior insulation
Mechanical systems					
Heat supply	Forced-air system with fan-coil	Forced-air coupled to heat pump	Forced-air system	Hydronic radiant floors	Hydronic radiant floors
GSHP	14.1 kW	-	Yes	-	Yes
Photovoltaic panels	8.3 kW	98 m²	-	-	Wiring installed for future implementation
Solar thermal collectors	5.8 m² evacuated tube water solar collector	Flate plate water solar collector, area n/a	-	Air solar collector for pre-heating and solar water heater (vacuum tubes)	-
Heat pump	-	Air-source heat pumps, one for DHW and one for heating	-	-	-
Other energy source	Electric backup for DHW	-	-	Electricity backup for space heating water	-
Mechanical ventilation	HRV, 60 L/s	HRV	HRV	n/a	Dual core HRV
Solar radiation control	Overhangs	Overhangs	-	n/a	Overhangs and other shading systems

Project	**Maison Orfie**	**Ecologis Karine O'Cain**
Location	Eastman, QC	Trois-Rivières, QC
Project	LEED Platine	LEED Platine
Heated area (m²)	128.5	406 (6 units)
Thermal resistance (m².K/W)		
Above ground walls	4.31	3.69
Roof	7.22	8.09
Foundation walls	2.99	2.90
Foundation floor	0.88	1.40
Envelope components		
Thermal mass	Concrete floors	-
Airtightness ($ACH_{50\ Pa}$)	<2.5	
Window type	n/a	Double argon-filled
Wall framing	2 per 6 wood studs	2 per 6 wood studs
Mechanical systems		
Heat supply	Hydronic radiant floors and radiant fireplace	Water radiators (60 to 100°C)
GSHP	-	-
Photovoltaic panels	-	-
Solar thermal collectors	-	8 rooftop collectors (22 m²) for DHW and heating
Heat pump	-	-
Other energy source	Wood (fireplace)	Electric backup
Mechanical ventilation	HRV, rate n/a	n/a
Solar radiation control	Louvered overhangs on south windows	-

Sources, by project:

Inspiration by Minto: Canada Mortgage and Housing Corporation (2010c)

Alstonvale: Candanedo J.A. et al (2009), Canada Mortgage and Housing Corporation (2010b)

Ecoterra: Solar Buildings Research Network (2011), Canada Mortgage and Housing Corporation (2010a)

Abondance Le Soleil: Canada Mortgage and Housing Corporation (2011a)

Riverdale: Riverdale Net Zero Project (N/A), Canada Housing and Mortgage Corporation (2008a)

Avalon Discovery 3: Canada Housing and Mortgage Corporation (2008b)

Now House Retrofit: Canada Housing and Mortgage Corporation (2008c)

Laebon CHESS Project: Canada Housing and Mortgage Corporation (2011b)

Urban Ecology: Canada Mortgage and Housing Corporation (2010d)

Green Dream Home: Canada Mortgage and Housing Corporation (2010e)

Harmony House: Harmony House (2011)

Écohabitation: Boulze D. (2007)

BL Écoconstruction : BL Écoconstruction (N/A)

Rideau Residence: Defendorf (2011)

Maison Orfie: Fauteux (2010)

Écologis Karine O'Cain: Tellier Yves. Email to Marie-Claude Hamelin, with architectural drawings attached. July 21-23, 2011

10. Appendix B: Life-cycle data for the house envelope

Sample of embodied energy data for assemblies, divided into life cycle phase, with their source.

		Primary energy (MJ) used per unit					
Material description	**Unit**	**Manufacturing**	**Construction**	**Maintenance**	**End of life**	**Total**	**Source**
Insulation							
Fiberglass batt	0.0254 m³	13.80	0.06	0.00	0.05	13.91	ATHENA Institute, 2008
Blown cellulose	0.0254 m³	1.32	0.15	0.00	0.05	1.52	ATHENA Institute, 2008
Extruded polystyrene	0.0254 m³	73.90	0.12	0.00	0.10	74.12	ATHENA Institute, 2008
Sprayed polyurethane	0.0254 m³	112.93	unknown	0.00	unknown	112.93	Petersdorff, 2002
Sprayed polyisocyanurate	0.0254 m³	61.50	0.43	0.00	0.07	62.00	ATHENA Institute, 2008
Foundations							
Concrete, average fly ash, 30 Mpa	1 m³	15500	1390	0	741	17631	ATHENA Institute, 2008
Foundation footings 467 mm per 200 mm, #15 rebars	27.6 m linear	6610	643	0	192	7445	ATHENA Institute, 2008
Bitumen layer (2 mm)	1 m³	2475	unknown	unknown	unknown	2524.5	Alcorn, 2003
Vinyl siding	1 m²	96.7	1.43	0	0.19	98.32	ATHENA Institute, 2008
2x3 horizontal wood furring, 400 mm c/c spacing	0.467 m³						ATHENA Institute, 2008
2x3 wall frame with gypsum	78 m²	4680	765	0	68.5	5513.5	ATHENA Institute, 2008
2x4 wall frame with gypsum	78 m²	5000	800	0	72.1	5872.1	ATHENA Institute, 2008
2x6 wall frame with gypsum	78 m²	5660	875	0	79.3	6614.3	ATHENA Institute, 2008
2x8 wall frame with gypsum	78 m²	6230	936	0	85.6	7251.6	ATHENA Institute, 2008
6 mil polyethyle vapor barrier	1 m²	38.7	0.1	0	0.01	38.81	ATHENA Institute, 2008
East or West wall framing (including gypsum, vapor barrier, OSB and windows structure)							
Double 2x4 studs, 600 mm c/c spacing	49.21 m²	8375.00	687.30	0.00	64.80	9127.10	ATHENA Institute, 2008
2x6 studs, 600 mm c/c spacing	49.21 m²	8020	654	0	61.4	8735.4	ATHENA Institute, 2008
2x8 studs, 600 mm c/c spacing	49.21 m²	8360	690	0	65.1	9115.1	ATHENA Institute, 2008
North wall framing (including gypsum, vapor barrier and OSB)							
Double 2x4 studs, 600 mm c/c spacing	87.80 m²	16390.00	1323.00	0.00	124.20	17837.20	ATHENA Institute, 2008
2x6 studs, 600 mm c/c spacing	87.80 m²	15800.00	1270.00	0.00	119.00	17189.00	ATHENA Institute, 2008
2x8 studs, 600 mm c/c spacing	87.80 m²	16300	1330	0	125	17755	ATHENA Institute, 2008
Roof framing (including gypsum and plywood)							
2x6 studs, 600 mm c/c spacing	64 m²	7450	1260	0	80.8	8790.8	ATHENA Institute, 2008
2x8 studs, 600 mm c/c spacing	64 m²	7860	1300	0	85.3	9245.3	ATHENA Institute, 2008
Exterior walls and roof (other elements)							
41 mm x 41 mm metal studs	1000 kg	64700	156	0	38.6	64894.6	ATHENA Institute, 2008
2 per 3 inch wood furring	1 m³	1680	180	0	18.4	1878.4	ATHENA Institute, 2008
Commercial steel roofing	64 m²	38400	193	68600	10.7	107203.7	ATHENA Institute, 2008
8 mm fiber cement cladding	1 kg	11.7	unknown	unknown	unknown	11.7	Hammonds and Jones, 2008
Interior partition walls (with gypsum on both sides)							
2x4 studs, 600 mm c/c spacing	2 m²	227.00	38.00	0.00	3.40	268.40	ATHENA Institute, 2008
Floors							
11.5 in I-joist structure (first floor)	46.4 m²	7560	1180	0	41.5	8781.5	ATHENA Institute, 2008
11.5 in I-joist structure (second floor)	37.5 m²	6090	877	0	31.8	6998.8	ATHENA Institute, 2008
Lightweight concrete	1 m³	1309	unknown	unknown	unknown	1309	Hammonds and Jones, 2008
Hardwood floor	1 m³	1680	180	0	18.4	1878.4	ATHENA Institute, 2008
Windows							
Double glazing, low-e, argon-filled	1 m²	140	14.92	0	2.38	157.3	ATHENA Institute, 2008
Double glazing	1 m²	139.4	14.92	0	2.38	156.7	ATHENA Institute, 2008
Triple glazing, double low-e, argon-filled (Twice double glazing minus half a double glazing)	1 m²	210.3	22.38	0	3.57	236.25	ATHENA Institute, 2008
Fiberglass framing	1 m³	60600	unknown	unknown	unknown	60600	Chen et al., 2001
Outside framing of modules							
Large kiln-dried lumber	1 m³	1760	595	0	15.2	2370.2	ATHENA Institute, 2008

Assumptions for service life and waste factors, as modeled by Athena Impact Estimator

Source: Athena Sustainable Materials Institute, 2002 (unless otherwise noted)

Material	**Service life (years)**	**Waste factor (%)**
Bitumen	50	2
Blown cellulose	50	5
Commercial steel roofing	50[1]	10
Engineered wood I-joist	50	1
Extruded polystyrene	50	5
Fiber cement cladding	50[2]	7
Fiberglass batt	50	5
Fiberglass window framing	50	0
Foil-faced polyisocyanurate	50	5
Galvanized steel sheet (z-bars)	50	1
Glulam beams	50	1
Gypsum board	50	10
Hardwood floors	25	8
Latex paint	8	2
Large lumber (kiln dried)	50	5
Lightweight concrete	50	5
Triple argon-filled glazing with low-e coatings	25	1
Oriented strandboard	50	5
Plywood	50	5
Polyethylene membrane	50	2
Small lumber (kiln dried)	50	8
Sprayed polyurethane	50	5
Structural concrete	50	5
Vinyl siding	35	7

[1] Source: Ideal Roofing Warranty, available at <http://www.idealroofing.com/PDF/Perspectra_&_WeatherX_Garantie.pdf> [Last accessed August 18th, 2011]

Cost data for envelope assemblies

	Foundation footings 18'' per 8'', #15 rebars, 4000 psi concrete				Source: Assembly p.118
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
27.6	1 lin. m	29.96	20.77	50.73	1400.25
	Concrete wall systems, 8" thick, 4000 psi concrete, insulation exlcuded				Source: Assembly p. 122
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
78	1 m²	88.61	73.49	162.10	12643.84
	Basement wall interior finish (framing 2 x 4 at 24'', gypsum and paint)				Source: Assembly p. 154
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
78	1 m²	20.47	26.26	46.73	3644.55
	Basement wall interior finish (framing 2 x 6 at 24'', gypsum and paint)				Source: Assembly p. 154
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
78	1 m²	24.32	27.26	51.57	4022.78
	Basement wall interior finish (framing 2 x 8 at 24'', gypsum and paint)				Source: Assembly p. 154 + 137
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
78	1 m²	30.65	28.76	59.41	4634.23
	Floor slab, 4" thick, 4000 psi concrete, insulation excluded				Source: Assembly p. 126
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
46.4	1 m²	30.59	15.18	45.77	2123.52
	Exterior finish system for ext insulation of foundation			Source: Assembly	Source: Assembly p. 166
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
38.9	1 m²	54.92	32.85	87.77	3414.14
	Floor I-joist, 9 1/2" , 16" o.c., 3/4'' thick plywood			Source: Assembly p.132	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
84	1 m²	48.00	24.56	72.56	6094.86
	Floor I-joist, 11 1/2" , 16" o.c., 3/4'' thick plywood			Source: Assembly p.132	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
84	1 m²	55.84	25.86	81.70	6862.68

	Exterior wall framing, 2" x 4", 24" o.c.			Source: Assembly p.136	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	12.15	12.18	24.33	4526.15
	Exterior wall framing, 2" x 6", 24" o.c.			Source: Assembly p.136	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	15.99	13.08	29.08	5408.47
	Exterior wall framing, 2" x 8", 24" o.c.			Source: Assembly p.136	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	20.16	14.58	34.73	6460.41
	Exterior wall framing, double 2" x 4", 24" o.c.			Source: Assembly p.136	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	19.23	21.46	40.69	7568.26
	Exterior wall interior finish (gypsum)				
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	12.93	16.37	29.30	5913.10
	Exterior wall exterior finish (fiber cement)			Source: architect	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	29.43	45.14	74.57	13870.87
	Exterior wall outside painting			Source: Assembly p.164	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	1.84	7.48	9.33	1734.86
	Windows and door headers 2" x8" - east or west windows			Source: Assembly p.137	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
1	1.5 m (5 ft)	22.87	43.60	66.46	66.46
	Windows and door headers 2" x 6" - 1 door			Source: Assembly p.137	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
1	1 m (3 ft)	4.97	12.48	17.45	17.45

	Roof framing 0-4/12 pitch, 2" x 6" 24" o.c.			Source: Assembly p. 148	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
64	1 m²	22.00	19.47	41.47	2654.00
	Roof framing 0-4/12 pitch, 2" x 8" 24" o.c.			Source: Assembly p. 148	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
64	1 m²	25.38	20.57	45.95	2940.55
	Roof exterior finish (steel roofing)			Source: architect	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
64	1 m²	29.43	33.86	63.29	4050.50
	Roof interior finition (drywall)				
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
40	1 m²	12.93	16.37	29.30	1171.96
	Partition wall framing, 2"x 4", 24" o.c.			Source: Assembly p. 154	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
45.5	1 m²	7.54	9.88	17.42	792.82
	Partition wall, 1/2" drywall taped and finished (both sides)			Source: Assembly p.214	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
45.5	1 m²	25.85	32.75	58.60	2666.21
	Repainting walls (2 layers)			Source: Assembly p.214	
	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
186	1 m²	2.56	4.47	7.03	1307.78
	Roof structure			Source: Happy Modular in-house estimate	
Qty	Cost				
1	14077	all inclusive			
	Concrete floors			Source: Happy Modular in-house estimate	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
84	1 m² at 5 cm	220.10	labour included	220.10	18488.66
84	1 m² at 10 cm	235.14	labour included	235.14	19751.86
	Hard wood floors			Source: Happy Modular in-house estimate	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
84	1 m²	103.01	labour included	103.01	8652.92

	Triple-glazed low-e windows, fibreglass framing, non-operable			Source: Happy Modular in-house estimate	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
Variable	1 m^2	809.34	labour included	809.34	-
	Triple-glazed low-e windows, fibreglass framing, operable			Source: Happy Modular in-house estimate	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
Variable	1 m^2	969.89	labour included	969.89	-
	Triple-glazed low-e windows, fibreglass framing, operable			Source: Happy Modular in-house estimate	
Qty	Unit	Mat. cost	Inst. cost	Total cost per unit	Total cost
Variable	1 m^2	969.89	labour included	969.89	-

11. Appendix C: Performance data for mechanical systems

Performance table for York TCGF18S41S3 - AC unit (Johnson Controls, 2012)

COOLING PERFORMANCE DATA																
AIR CONDITIONER MODEL NO.		TCGF18S41S3(E)														
INDOOR COIL MODEL NO.		FC/MC/PC32														
CONDENSING ENTERING AIR TEMPERATURE	IDCFM	450					600					750				
	ID DB (°F)	80	80	75	80	80	80	80	75	80	80	80	80	75	80	80
	ID WB (°F)	57	62	62	67	72	57	62	62	67	72	57	62	62	67	72
65	T.C.	16.2	17.9	17.6	20.0	22.3	18.0	18.8	18.6	20.9	23.6	19.8	19.8	19.6	21.9	25.0
	S.C.	16.2	14.9	12.3	12.8	10.1	18.0	17.3	14.2	14.5	11.4	19.8	19.7	16.1	16.3	12.6
	KW	1.00	0.98	1.00	0.99	0.98	0.99	0.99	0.99	0.98	0.97	0.99	0.99	0.99	0.97	0.96
75	T.C.	15.3	16.9	16.8	19.0	21.2	17.1	18.0	17.7	19.9	22.4	19.0	19.1	18.7	20.8	23.6
	S.C.	15.3	14.3	11.9	12.2	9.8	17.1	16.7	13.7	13.9	11.0	19.0	19.1	15.6	15.7	12.2
	KW	1.17	1.15	1.17	1.16	1.14	1.16	1.15	1.16	1.15	1.13	1.14	1.14	1.15	1.14	1.12
85	T.C.	14.4	16.0	15.9	17.9	20.2	16.3	17.1	16.8	18.8	21.2	18.1	18.3	17.7	19.8	22.3
	S.C.	14.4	13.8	11.4	11.6	9.4	16.3	16.1	13.3	13.4	10.6	18.1	18.3	15.1	15.1	11.8
	KW	1.35	1.32	1.33	1.33	1.30	1.32	1.31	1.32	1.31	1.29	1.29	1.29	1.31	1.30	1.28
95	T.C.	13.5	15.1	15.0	16.9	19.2	15.4	16.3	15.9	17.8	20.1	17.3	17.5	16.8	18.7	20.9
	S.C.	13.5	13.2	11.0	11.0	9.0	15.4	15.5	12.8	12.8	10.2	17.3	17.5	14.6	14.6	11.3
	KW	1.52	1.50	1.50	1.50	1.46	1.48	1.47	1.48	1.48	1.45	1.45	1.45	1.47	1.47	1.44
105	T.C.	12.9	14.1	13.9	15.8	18.0	14.6	15.3	14.7	16.6	18.7	16.2	16.4	15.5	17.4	19.4
	S.C.	12.9	12.7	10.5	10.6	8.6	14.6	14.7	12.2	12.4	9.6	16.2	16.4	14.0	14.2	10.7
	KW	1.80	1.79	1.81	1.80	1.74	1.77	1.75	1.78	1.77	1.74	1.73	1.72	1.75	1.74	1.73
115	T.C.	12.4	13.2	12.9	14.7	16.8	13.7	14.3	13.6	15.5	17.3	15.1	15.4	14.2	16.2	17.9
	S.C.	12.4	12.3	10.1	10.2	8.2	13.7	14.0	11.7	12.0	9.1	15.1	15.4	13.3	13.8	10.1
	KW	2.07	2.07	2.11	2.09	2.01	2.04	2.02	2.06	2.05	2.01	2.00	1.98	2.02	2.01	2.01
125	T.C.	11.9	12.2	11.9	13.6	15.6	12.9	13.3	12.4	14.3	16.0	13.9	14.3	12.9	15.0	16.4
	S.C.	11.9	11.9	9.6	9.9	7.7	12.9	13.2	11.1	11.6	8.6	13.9	14.3	12.7	13.4	9.5
	KW	2.34	2.36	2.42	2.38	2.28	2.31	2.30	2.35	2.33	2.29	2.28	2.24	2.29	2.28	2.29
NOTE: ALL CAPACITIES INCLUDE INDOOR FAN HEAT. KW VALUES ARE FOR THE SYSTEM (OUTDOOR + INDOOR).																

Performance table for York THJF18S41S1 – ASHP (Johnson Controls, 2011)

COOLING PERFORMANCE DATA																
CONDENSING UNIT MODEL NO.	YHJF18S41S1															
INDOOR COIL MODEL NO.	AHX30															
CONDENSING ENTERING AIR TEMPERATURE	IDCFM	400					600					800				
	ID DB (°F)	80	80	75	80	80	80	80	75	80	80	80	80	75	80	80
	ID WB (°F)	57	62	62	67	72	57	62	62	67	72	57	62	62	67	72
65	T.C.	17.2	18.8	18.8	20.5	22.2	19.2	19.9	20.1	21.7	22.9	21.2	20.9	21.3	22.8	23.6
	S.C.	16.8	14.9	12.9	12.9	11.0	18.8	17.7	15.2	14.7	11.7	20.8	20.5	17.4	16.5	12.5
	KW	0.86	0.89	0.89	0.88	0.88	0.94	0.96	0.96	0.95	0.95	1.02	1.02	1.02	1.02	1.02
75	T.C.	16.4	17.9	17.9	19.7	21.3	18.4	19.1	19.0	20.8	22.1	20.4	20.2	20.2	21.8	22.9
	S.C.	16.1	14.5	12.5	12.5	10.5	18.0	17.1	14.8	14.4	11.5	20.0	19.8	17.0	16.3	12.4
	KW	0.99	1.02	1.02	1.02	1.02	1.08	1.09	1.09	1.09	1.10	1.17	1.16	1.17	1.17	1.18
85	T.C.	15.7	17.0	17.0	18.9	20.4	17.7	18.3	18.0	19.9	21.3	19.6	19.5	19.1	20.8	22.1
	S.C.	15.4	14.1	12.1	12.1	10.1	17.3	16.6	14.3	14.2	11.2	19.2	19.1	16.6	16.2	12.2
	KW	1.12	1.14	1.14	1.15	1.17	1.22	1.23	1.22	1.24	1.25	1.31	1.31	1.31	1.32	1.33
95	T.C.	15.0	16.1	16.1	18.1	19.6	16.9	17.4	17.0	19.0	20.4	18.8	18.8	18.0	19.8	21.3
	S.C.	14.7	13.7	11.6	11.8	9.7	16.5	16.0	13.9	13.9	10.9	18.4	18.4	16.2	16.0	12.1
	KW	1.25	1.26	1.26	1.29	1.31	1.36	1.36	1.36	1.38	1.40	1.46	1.46	1.45	1.46	1.49
105	T.C.	14.0	14.7	14.8	16.7	18.4	15.9	16.2	15.7	17.6	19.2	17.7	17.7	16.6	18.5	20.1
	S.C.	13.7	13.1	11.0	11.2	9.2	15.5	15.2	13.3	13.4	10.4	17.3	17.3	15.6	15.6	11.6
	KW	1.41	1.42	1.42	1.45	1.48	1.52	1.52	1.51	1.54	1.57	1.63	1.63	1.61	1.63	1.65
115	T.C.	13.1	13.4	13.4	15.4	17.2	14.8	15.0	14.4	16.2	18.0	16.6	16.6	15.3	17.1	18.8
	S.C.	12.8	12.5	10.5	10.6	8.7	14.5	14.4	12.7	12.9	9.9	16.2	16.2	15.0	15.1	11.2
	KW	1.56	1.57	1.57	1.60	1.65	1.68	1.68	1.67	1.70	1.74	1.80	1.80	1.77	1.80	1.82
125	T.C.	12.2	12.1	12.1	14.0	16.1	13.8	13.8	13.0	14.9	16.8	15.5	15.5	14.0	15.7	17.5
	S.C.	11.9	11.9	9.9	10.1	8.2	13.5	13.5	12.1	12.3	9.5	15.1	15.1	14.0	14.6	10.7
	KW	1.72	1.72	1.72	1.76	1.82	1.84	1.84	1.82	1.87	1.90	1.97	1.97	1.92	1.97	1.99
NOTE: ALL CAPACITIES INCLUDE INDOOR FAN HEAT. KW VALUES ARE FOR THE SYSTEM (OUTDOOR + INDOOR).																

HEATING PERFORMANCE DATA										
CONDENSING UNIT MODEL NO	YHJF18S41S1									
EVAPORATOR COIL MODEL NO	AHX30									
AIR TEMP. ENTERING OUTDOOR UNIT	AIR TEMP. ENTERING INDOOR COIL	ID CFM								
		450			600			750		
		MBH	COP	KW	MBH	COP	KW	MBH	COP	KW
60	60	20.9	4.6	1.34	22.0	5.0	1.30	23.0	5.4	1.25
	70	20.3	4.0	1.48	21.3	4.3	1.44	22.3	4.7	1.39
	80	19.7	3.5	1.63	20.7	3.8	1.58	21.6	4.2	1.52
47	60	18.4	4.2	1.29	18.9	4.4	1.27	19.5	4.6	1.24
	70	17.5	3.6	1.43	18.1	3.9	1.37	18.8	4.2	1.31
	80	16.6	3.1	1.57	17.3	3.3	1.54	18.0	3.5	1.50
40	60	16.4	3.8	1.27	17.0	4.0	1.25	17.5	4.2	1.23
	70	15.9	3.3	1.40	16.5	3.5	1.38	17.1	3.7	1.36
	80	15.4	3.0	1.53	16.0	3.1	1.51	16.6	3.3	1.48
30	60	14.4	3.4	1.23	14.8	3.5	1.23	15.2	3.6	1.22
	70	13.9	3.0	1.36	14.3	3.1	1.35	14.6	3.2	1.34
	80	13.5	2.7	1.49	13.8	2.7	1.48	14.1	2.8	1.47
17	60	11.4	2.8	1.18	11.7	2.9	1.19	11.9	2.9	1.20
	70	10.6	2.4	1.29	10.9	2.5	1.27	11.2	2.6	1.24
	80	10.2	2.1	1.42	10.5	2.2	1.39	10.8	2.3	1.35
10	60	9.5	2.5	1.13	9.6	2.5	1.12	9.7	2.6	1.11
	70	9.1	2.1	1.26	9.3	2.2	1.24	9.5	2.3	1.22
	80	8.6	1.8	1.39	8.9	1.9	1.37	9.3	2.0	1.34
NOTE: ALL CAPACITIES ARE NET, WITH INDOOR FAN HEAT ALREADY DEDUCTED. KW VALUES ARE FOR THE SYSTEM (OUTDOOR + INDOOR).										

Performance table for Mitsubishi Zuba – CCASHP (Mitsubishi Electric Sales Canada, 2012)

Outdoor temperature (°C)	Heating capacity (kW)	Electrical input (kW)	COP
15.6	13.48	3.81	3.5
12.8	12.03	3.65	3.3
10.0	11.64	3.52	3.3
7.2	11.32	3.30	3.4
4.4	11.14	3.23	3.4
1.7	11.14	4.04	2.8
-1.1	11.14	4.68	2.4
-3.9	11.14	5.17	2.2
-6.7	11.14	5.49	2.0
-9.4	11.14	5.75	1.9
-12.2	11.14	5.91	1.9
-15.0	11.14	6.04	1.8
-17.8	10.47	6.11	1.7
-20.6	9.91	6.07	1.6
-23.3	9.36	6.14	1.5
-26.1	8.69	6.20	1.4
-28.9	8.02	6.23	1.3
-31.7	7.35	6.27	1.2
-34.4	6.68	6.30	1.1
-37.2	6.01	6.33	0.9

Performance table for Geocomfort XT series, model 024 – GSHP (Enertech Global, 2011)

Part Load, 700 CFM Cooling / 700 CFM Heating

				Heating							Cooling							
EWT °F	Flow GPM	WPD PSI	WPD FT	Airflow CFM	HC MBtuh	HE MBtuh	LAT °F	kW	COP W/W	DH MBtuh	Airflow CFM	TC MBtuh	SC MBtuh	S/T	HR MBtuh	kW	EER Btuh/W	DH MBtuh
25	6.0	1.6	3.7	700	13.6	9.5	88.0	1.21	3.29	1.8	Operation Not Recommended							
				600	13.4	9.0	90.7	1.30	3.02	1.8								
30	4.3	0.8	1.9	700	14.7	10.5	89.4	1.22	3.53	1.9								
				600	14.4	9.9	92.2	1.31	3.22	1.9								
	5.0	1.0	2.4	700	14.9	10.7	89.7	1.22	3.58	1.9								
				600	14.6	10.1	92.5	1.31	3.27	1.9								
	6.0	1.6	3.7	700	15.0	10.8	89.8	1.22	3.60	1.9								
				600	14.8	10.3	92.8	1.31	3.31	1.9								
40	4.3	0.8	1.9	700	17.0	12.8	92.5	1.22	4.08	2.2								
				600	16.7	12.2	95.8	1.31	3.74	2.2								
	5.0	1.1	2.5	700	17.2	13.0	92.8	1.22	4.13	2.3								
				600	16.9	12.4	96.1	1.31	3.78	2.3								
	6.0	1.6	3.8	700	17.4	13.2	93.0	1.22	4.18	2.3								
				600	17.1	12.6	96.4	1.31	3.82	2.4								
50	4.3	0.8	1.9	700	19.3	15.1	95.5	1.22	4.64	2.5	700	22.3	15.7	0.70	24.8	0.74	30.1	1.9
				600	19.0	14.5	99.3	1.31	4.25	2.5	600	21.1	14.3	0.68	23.6	0.72	29.3	1.7
	5.0	1.1	2.5	700	19.6	15.4	95.9	1.22	4.71	2.7	700	22.4	15.8	0.71	24.9	0.72	31.1	1.8
				600	19.2	14.7	99.6	1.31	4.29	2.6	600	21.2	14.4	0.68	23.6	0.71	29.9	1.6
	6.0	1.6	3.8	700	19.8	15.6	96.2	1.22	4.76	2.6	700	22.4	15.8	0.71	24.8	0.71	31.5	1.6
				600	19.4	14.9	99.9	1.31	4.34	2.5	600	21.2	14.4	0.68	23.6	0.70	30.3	1.5
60	4.3	0.8	1.8	700	21.8	17.6	98.8	1.22	5.24	2.9	700	21.3	15.2	0.71	24.2	0.84	25.4	2.2
				600	21.4	16.9	103.0	1.31	4.79	3.0	600	20.2	13.9	0.69	23.0	0.83	24.3	2.0
	5.0	1.0	2.4	700	22.1	17.9	99.2	1.22	5.31	3.0	700	21.4	15.3	0.71	24.2	0.83	25.8	2.1
				600	21.7	17.2	103.5	1.31	4.85	2.9	600	20.3	14.0	0.69	23.1	0.81	25.1	1.9
	6.0	1.6	3.6	700	22.3	18.1	99.5	1.22	5.36	2.9	700	21.4	15.3	0.71	24.2	0.82	26.1	2.0
				600	22.0	17.5	104.0	1.31	4.92	3.1	600	20.3	14.0	0.69	23.0	0.80	25.4	1.8
70	4.3	0.7	1.7	700	24.3	20.1	102.1	1.24	5.74	3.3	700	20.4	14.8	0.73	23.6	0.95	21.5	2.5
				600	23.9	19.4	106.9	1.33	5.27	3.2	600	19.3	13.4	0.69	22.5	0.93	20.8	2.3
	5.0	1.0	2.2	700	24.6	20.4	102.5	1.24	5.81	3.3	700	20.5	14.8	0.72	23.7	0.94	21.8	2.4
				600	24.2	19.7	107.3	1.33	5.33	3.2	600	19.4	13.5	0.70	22.5	0.92	21.1	2.2
	6.0	1.4	3.3	700	24.9	20.7	102.9	1.24	5.88	3.3	700	20.5	14.8	0.72	23.6	0.92	22.3	2.3
				600	24.5	20.0	107.8	1.33	5.40	3.2	600	19.4	13.5	0.70	22.5	0.91	21.3	2.1
80	4.3	0.7	1.6	700	26.6	22.3	105.2	1.25	6.23	3.6	700	19.3	14.4	0.75	23.0	1.08	17.9	3.0
				600	26.1	21.5	110.3	1.35	5.66	3.6	600	18.3	13.1	0.72	21.9	1.06	17.3	2.7
	5.0	0.9	2.0	700	27.0	22.7	105.7	1.25	6.33	3.6	700	19.4	14.5	0.75	23.0	1.06	18.3	2.9
				600	26.5	21.9	110.9	1.35	5.75	3.6	600	18.3	13.2	0.72	21.8	1.04	17.6	2.6
	6.0	1.3	3.1	700	27.2	22.9	106.0	1.25	6.38	3.6	700	19.4	14.5	0.75	23.0	1.05	18.5	2.7
				600	26.8	22.2	111.4	1.35	5.82	3.8	600	18.3	13.2	0.72	21.8	1.03	17.8	2.5
90	4.3	0.7	1.5	700	28.9	24.6	108.2	1.27	6.67	3.9	700	18.1	14.1	0.78	22.3	1.22	14.8	3.4
				600	28.4	23.8	113.8	1.36	6.12	3.8	600	17.2	12.8	0.74	21.3	1.20	14.3	3.1
	5.0	0.9	2.0	700	29.3	25.0	108.8	1.26	6.81	4.0	700	18.2	14.1	0.77	22.3	1.20	15.2	3.3
				600	28.8	24.2	114.4	1.36	6.20	3.9	600	17.2	12.9	0.75	21.2	1.18	14.6	3.0
	6.0	1.3	3.0	700	29.6	25.3	109.2	1.26	6.88	4.0	700	18.2	14.2	0.78	22.3	1.19	15.3	3.1
				600	29.1	24.5	114.9	1.36	6.27	3.9	600	17.2	12.9	0.75	21.2	1.16	14.8	2.8
100	4.3	0.7	1.6	Operation Not Recommended							700	17.0	13.6	0.80	21.7	1.39	12.2	3.7
											600	16.0	12.4	0.78	20.6	1.36	11.8	3.4
	5.0	0.9	2.0								700	17.0	13.7	0.81	21.6	1.36	12.5	3.6
											600	16.1	12.4	0.77	20.6	1.33	12.1	3.3
	6.0	1.3	3.1								700	17.0	13.7	0.81	21.6	1.35	12.6	3.5
											600	16.1	12.4	0.77	20.6	1.32	12.2	3.2
110	4.3	0.7	1.6								700	15.8	13.1	0.83	21.1	1.56	10.1	4.1
											600	14.9	11.9	0.80	20.1	1.53	9.7	3.7
	5.0	0.9	2.1								700	15.9	13.2	0.83	21.1	1.53	10.4	4.0
											600	15.0	12.0	0.80	20.1	1.50	10.0	3.6
	6.0	1.4	3.2								700	15.9	13.2	0.83	21.1	1.52	10.5	4.0
											600	15.0	12.0	0.80	20.1	1.48	10.1	3.6

Heating data based on 70F EAT; Cooling data based on 80/67F EAT. See Correction Factors on page 20 for different conditions.

Performance table for Geocomfort XT series, model 024 – GSHP – Continued

Full Load, 950 CFM Cooling / 950 CFM Heating

EWT °F	Flow GPM	WPD PSI	WPD FT	Heating Airflow CFM	Heating HC MBtuh	Heating HE MBtuh	Heating LAT °F	Heating kW	Heating COP W/W	Heating DH MBtuh	Cooling Airflow CFM	Cooling TC MBtuh	Cooling SC MBtuh	Cooling S/T	Cooling HR MBtuh	Cooling kW	Cooling EER Btuh/W	Cooling DH MBtuh
25	7.0	2.6	6.1	950	18.9	13.7	88.4	1.53	3.62	2.5	Operation Not Recommended							
				800	18.7	13.2	91.6	1.62	3.38	2.5								
30	5.0	1.2	2.8	950	20.4	15.1	89.9	1.55	3.86	2.7								
				800	20.1	14.5	93.3	1.64	3.59	2.7								
	6.0	1.8	4.2	950	20.7	15.4	90.2	1.55	3.91	2.7								
				800	20.4	14.8	93.6	1.64	3.64	2.7								
	7.0	2.6	5.9	950	20.9	15.6	90.4	1.55	3.95	2.7								
				800	20.6	15.0	93.8	1.64	3.68	2.7								
40	5.0	1.1	2.6	950	23.4	18.0	92.8	1.58	4.34	3.1								
				800	23.1	17.4	96.7	1.67	4.05	3.1								
	6.0	1.7	3.9	950	23.7	18.3	93.1	1.58	4.39	3.2								
				800	23.4	17.7	97.1	1.67	4.11	3.1								
	7.0	2.4	5.5	950	23.9	18.5	93.3	1.58	4.43	3.2								
				800	23.6	17.9	97.3	1.67	4.14	3.3								
50	5.0	1.1	2.5	950	26.4	20.9	95.7	1.61	4.80	3.5	950	30.5	21.0	0.69	34.5	1.17	26.1	2.5
				800	26.0	20.2	100.1	1.71	4.45	3.4	800	29.2	19.2	0.66	33.1	1.14	25.6	2.3
	6.0	1.6	3.8	950	26.8	21.3	96.1	1.61	4.88	3.6	950	30.7	21.0	0.68	34.6	1.15	26.7	2.3
				800	26.4	20.6	100.6	1.71	4.52	3.5	800	29.4	19.2	0.65	33.2	1.12	26.3	2.1
	7.0	2.3	5.3	950	27.0	21.5	96.3	1.61	4.91	3.6	950	30.7	21.0	0.68	34.6	1.13	27.2	2.3
				800	26.6	20.8	100.8	1.71	4.56	3.5	800	29.4	19.2	0.65	33.2	1.11	26.5	2.1
60	5.0	1.1	2.5	950	29.7	24.0	98.9	1.66	5.24	3.9	950	29.4	20.7	0.70	33.9	1.31	22.4	3.1
				800	29.4	23.4	104.0	1.76	4.89	4.0	800	28.2	18.9	0.67	32.6	1.28	22.0	2.8
	6.0	1.6	3.8	950	30.2	24.5	99.4	1.66	5.33	4.0	950	29.6	20.7	0.70	34.0	1.29	22.9	2.8
				800	29.8	23.8	104.5	1.77	4.93	4.0	800	28.3	18.9	0.67	32.6	1.26	22.5	2.6
	7.0	2.3	5.3	950	30.4	24.7	99.6	1.66	5.37	4.0	950	29.6	20.7	0.70	33.9	1.27	23.3	2.7
				800	30.0	24.0	104.7	1.77	4.97	4.2	800	28.3	18.9	0.67	32.5	1.24	22.8	2.5
70	5.0	1.1	2.5	950	33.1	27.2	102.3	1.73	5.61	4.4	950	28.2	20.2	0.72	33.1	1.45	19.4	3.5
				800	32.7	26.4	107.8	1.84	5.21	4.3	800	27.0	18.5	0.69	31.8	1.42	19.0	3.2
	6.0	1.7	3.8	950	33.6	27.7	102.7	1.73	5.69	4.5	950	28.3	20.2	0.71	33.2	1.43	19.8	3.4
				800	33.2	26.9	108.4	1.84	5.29	4.4	800	27.1	18.5	0.68	31.8	1.39	19.5	3.1
	7.0	2.3	5.4	950	33.8	27.9	102.9	1.73	5.72	4.5	950	28.3	20.2	0.71	33.1	1.41	20.1	3.2
				800	33.4	27.1	108.7	1.84	5.32	4.4	800	27.1	18.5	0.68	31.8	1.37	19.8	2.9
80	5.0	1.1	2.5	950	36.2	30.1	105.3	1.80	5.89	4.8	950	27.0	19.8	0.73	32.5	1.60	16.9	4.0
				800	35.8	29.2	111.4	1.92	5.46	4.8	800	25.9	18.1	0.70	31.2	1.56	16.6	3.7
	6.0	1.6	3.7	950	36.8	30.6	105.9	1.81	5.96	4.9	950	27.1	19.8	0.73	32.5	1.58	17.2	3.9
				800	36.3	29.7	112.0	1.92	5.54	4.9	800	26.0	18.1	0.70	31.3	1.54	16.9	3.6
	7.0	2.3	5.2	950	37.0	30.8	106.1	1.81	5.99	4.9	950	27.1	19.8	0.73	32.4	1.55	17.5	3.7
				800	36.6	30.0	112.4	1.92	5.59	5.1	800	26.0	18.1	0.70	31.2	1.52	17.1	3.4
90	5.0	1.0	2.2	950	39.4	33.0	108.4	1.88	6.14	5.2	950	25.6	19.3	0.75	31.6	1.77	14.5	4.6
				800	38.9	32.1	115.0	1.99	5.73	5.1	800	24.6	17.6	0.72	30.5	1.73	14.2	4.2
	6.0	1.5	3.4	950	39.9	33.5	108.9	1.88	6.22	5.3	950	25.8	19.3	0.75	31.7	1.74	14.8	4.4
				800	39.4	32.6	115.6	1.99	5.80	5.2	800	24.7	17.6	0.71	30.5	1.70	14.5	4.0
	7.0	2.1	4.7	950	40.2	33.8	109.2	1.88	6.27	5.4	950	25.8	19.3	0.75	31.7	1.72	15.0	4.3
				800	39.7	32.9	115.9	1.99	5.85	5.3	800	24.7	17.6	0.71	30.4	1.68	14.7	3.9
100	5.0	0.8	2.0	Operation Not Recommended							950	24.0	18.6	0.78	30.7	1.97	12.2	5.1
											800	23.0	17.0	0.74	29.6	1.92	12.0	4.7
	6.0	1.3	3.0								950	24.1	18.6	0.77	30.7	1.94	12.4	4.9
											800	23.1	17.0	0.74	29.6	1.89	12.2	4.5
	7.0	1.8	4.2								950	24.1	18.6	0.77	30.6	1.91	12.6	4.7
											800	23.1	17.0	0.74	29.4	1.86	12.4	4.3
110	5.0	0.9	2.1								950	22.2	17.8	0.80	29.6	2.17	10.2	5.6
											800	21.3	16.2	0.76	28.5	2.12	10.0	5.1
	6.0	1.4	3.2								950	22.3	17.8	0.80	29.6	2.13	10.5	5.4
											800	21.4	16.2	0.76	28.5	2.08	10.3	4.9
	7.0	1.9	4.5								950	22.3	17.8	0.80	29.5	2.10	10.6	5.2
											800	21.4	16.2	0.76	28.4	2.05	10.4	4.7

Heating data based on 70F EAT;Cooling data based on 80/67F EAT. See Correction Factors on page 20 for different conditions.

Performance table for Geocomfort XT series, model 024 – GSHP – Continued

Heating Correction Factors - Full Load

EAT°F	HC	HE	kW
50	1.0450	1.1136	0.8208
55	1.0347	1.0892	0.8567
60	1.0260	1.0640	0.9019
65	1.0089	1.0270	0.9497
70	1.0000	1.0000	1.0000
75	0.9924	0.9741	1.0527
80	0.9870	0.9653	1.0522

Heating Correction Factors - Part Load

EAT°F	HC	HE	kW
50	1.0480	1.1240	0.7839
55	1.0355	1.0943	0.8305
60	1.0246	1.0650	0.8837
65	1.0126	1.0330	0.9411
70	1.0000	1.0000	1.0000
75	0.9866	0.9661	1.0579
80	0.9613	0.9325	1.0513

Cooling Correction Factors

EAT (WB) °F	TC	HR	kW
55	0.8215	0.8293	0.8635
60	0.8955	0.9001	0.9205
65	0.9701	0.9715	0.9774
67	1.0000	1.0000	1.0000
70	1.0446	1.0425	1.0335
75	1.1179	1.1124	1.0878

Sensible Cooling Correction Factors

EAT (WB) °F	EAT (DB) °F				
	70	75	80	85	90
55	1.201	1.289			
60	0.943	1.067	1.192		
63	0.852	0.995	1.138		
65	0.797	0.952	1.106	1.261	
67	0.624	0.812	1.000	1.188	1.343
70		0.697	0.820	0.944	1.067
75			0.637	0.817	0.983

Gobi 408 solar collector standardized performance data

SOLAR COLLECTOR CERTIFICATION AND RATING	CERTIFIED SOLAR COLLECTOR	
SRCC OG-100	SUPPLIER:	Heliodyne, Inc. 4910 Seaport Avenue Richmond, CA 94804 USA
	MODEL:	GOBI 408 001
	COLLECTOR TYPE:	Glazed Flat-Plate
	CERTIFICATION#:	2010115D
	Original Certification Date:	28-MAR-11

COLLECTOR THERMAL PERFORMANCE RATING

Kilowatt-hours Per Panel Per Day				Thousands of BTU Per Panel Per Day			
CATEGORY (Ti-Ta)	CLEAR DAY (6.3 kWh / m^2.day)	MILDLY CLOUDY (4.7 kWh / m^2.day)	CLOUDY DAY (3.1 kWh / m^2.day)	CATEGORY (Ti-Ta)	CLEAR DAY (2000 Btu / ft^2.day)	MILDLY CLOUDY (1500 Btu / ft^2.day)	CLOUDY DAY (1000 Btu / ft^2.day)
A (-5 °C)	13.5	10.2	6.9	A (-9 °F)	46.2	34.9	23.7
B (5 °C)	12.3	9.0	5.7	B (9 °F)	42.0	30.8	19.5
C (20 °C)	10.5	7.3	4.0	C (36 °F)	35.8	24.8	13.8
D (50 °C)	7.2	4.1	1.3	D (90 °F)	24.5	14.2	4.6
E (80 °C)	4.3	1.6	0.0	E (144 °F)	14.6	5.6	0.0

A- Pool Heating (Warm Climate) B- Pool Heating (Cool Climate) C- Water Heating (Warm Climate) D- Water Heating (Cool Climate) E- Air Conditioning

COLLECTOR SPECIFICATIONS

Gross Area:	2.993 m^2	32.22 ft^2
Dry Weight:	46.3 kg	102. lb
Test Pressure:	1103. KPa	160. psig

Net Aperture Area:	2.78 m^2	29.93 ft^2
Fluid Capacity:	2.6 liter	0.7 gal

COLLECTOR MATERIALS

Frame: Aluminum

Cover (Outer): Tempered glass

Cover (Inner):

Pressure Drop

Flow		ΔP	
ml/s	gpm	Pa	in H_2O

Absorber Material: Tube - Copper / Plate - Aluminum

Absorber Coating: Selective coating

Insulation Side: Foam

Insulation Back: foam

TECHNICAL INFORMATION

Efficiency Equation [NOTE: Based on gross area and (P)=Ti-Ta]

	Efficiency Equation			Y INTERCEPT	SLOPE
SI Units:	η= 0.749	-3.69060 (P)/I	-0.00551 $(P)^2$/I	0.752	-4.029 W/m^2.°C
IP Units:	η= 0.749	-0.65010 (P)/I	-0.00054 $(P)^2$/I	0.752	-0.710 Btu/hr.ft^2.°F

Incident Angle Modifier [(S)=1/cosθ - 1, 0°<θ<=60°]

Kτα = 1	-0.078 (S)	-0.086 $(S)^2$
Kτα = 1	-0.17 (S)	Linear Fit

Test Fluid: Water

Test Flow Rate: 22.2 ml /s.m^2 0.0328 gpm/ft^2

REMARKS:

DHW heating capacity for GeoComfort 2 tons heatpump (Enertech Global, 2011)

Stage	Entering ground loop fluid temperature (°C)	Desuperheater DHW heating capacity (W)
Heating 1st	-3.9	528
	-1.1	557
	4.4	674
	10.0	762
	15.5	850
	21.1	967
Heating 2nd	-3.9	733
	-1.1	791
	4.4	938
	10.0	1055
	15.5	1172
	21.1	1319
Cooling 1st	-3.9	0
	-1.1	0
	4.4	0
	10.0	469
	15.5	586
	21.1	674
Cooling 2nd	-3.9	0
	-1.1	0
	4.4	0
	10.0	674
	15.5	791
	21.1	938

12. Appendix D: Borehole sizing

Spreadsheet as developed in Philippe et al., 2010.

		UNITS	Single borehole
1st SET OF INPUTS			
Ground loads			
peak hourly ground load	q_h	W	-2633
monthly ground load	q_m	W	-1042
yearly average ground load	q_y	W	-532
Ground properties			
thermal conductivity	k	$W.m^{-1}K^{-1}$	2
thermal diffusivity	α	$m^2.day^{-1}$	0.093
Undisturbed ground temperature	T_g	°C	6.3
Fluid properties			
thermal heat capacity	Cp	$J.kg^{-1}.K^{-1}$	3929
total mass flow rate per kW of peak hourly ground load	m_{fls}	$kg.s^{-1}.kW^{-1}$	0.084
max/min heat pump inlet temperature	T_{inHP}	°C	-2
Borehole characteristics			
borehole radius	r_{bore}	m	0.050
pipe inner radius	r_{pin}	m	0.0137
pipe outer radius	r_{pext}	m	0.0167
grout thermal conductivity	k_{grout}	$W.m^{-1}.K^{-1}$	1.50
pipe thermal conductivity	k_{pipe}	$W.m^{-1}.K^{-1}$	0.42
center-to-center distance between pipes	L_U	m	0.0580
internal convection coefficient	h_{conv}	$W.m^{-2}.K^{-1}$	1000
1st SET OF RESULTS			
Calculation of the effective borehole thermal resistance			
convective resistance	R_{conv}	$m.K.W^{-1}$	0.012
pipe resistance	R_p	$m.K.W^{-1}$	0.076
grout resistance	R_g	$m.K.W^{-1}$	0.049
effective borehole thermal resistance	R_b	$m.K.W^{-1}$	0.093
Calculation of the effective ground thermal resistances			
short term (6 hours pulse)	R_{6h}	$m.K.W^{-1}$	0.129
medium term (1 month pulse)	R_{1m}	$m.K.W^{-1}$	0.183
long term (10 years pulse)	R_{10y}	$m.K.W^{-1}$	0.191

Indicates an user input

13. Appendix E: Embodied energy data for mechanical systems

Embodied energy is estimated from a variety of sources from the scientific and technical literature. The following Appendix presents detailed calculations for the mechanical systems selected for the minimum LCC envelope. It was first assumed that air conditioning units, air-source heat pumps and cold climate air-source heat pumps all have similar components because they all use the vapour-compression cycle. A material mass inventory from Rey Martínez et al. (2011) is used for all those components, and it is multiplied by the ratio of the equipment weight (taken from manufacturer specifications) to the weight of the equipment described in this article. As Rey Martínez et al. did not account for the manufacturing energy of the unit, values given in a study by Greening and Azapagic (2012) are added to the embodied energy of materials.

Furnace with AC unit 1.5 tons						
Real weight/Rey Martinez et al. weight			2.053			
Material	**# of units Rey Martinez**	**# of units Actual equipment**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Cast iron	14.625	30.019	kg	25	750	Hammond and Jones 2011
Steel (low-alloy)	17.287	35.483	kg	20.1	713	Hammond and Jones 2011
Aluminum	9.767	20.048	kg	155	3107	Hammond and Jones 2011
Copper	5.579	11.451	kg	42	481	Hammond and Jones 2011
Nickel	0.586	1.203	kg	164	197	Hammond and Jones 2008
Lead	0.588	1.207	kg	25.21	30	Hammond and Jones 2011
Chromium	0.488	1.002	kg	83	83	Hammond and Jones 2008
Zinc	0.276	0.567	kg	61.9	35	Hammond and Jones 2008
Tin	0.006	0.012	kg	250	3	Hammond and Jones 2008
PVC	0.028	0.057	kg	76.7	4	Hammond and Jones 2008
HDPE	1.438	2.952	kg	76.7	226	Hammond and Jones 2008
R-134a refrigerant		2.450	kg	64	157	Campbell and McCulloch, 1998
Manufacturing	1212	2487.724	MJ	1	2488	Greening and Azapagic 2012
TOTAL					**8276**	
LC embodied energy (including replacements)					**27588**	-

ASHP 1.5 tons						
Real weight/Rey Martinez et al. weight			2.230			
Material	**# of units Rey Martinez**	**# of units Actual equipment**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Cast iron	14.625	32.617	kg	25	815	Hammond and Jones 2011
Steel (low-alloy)	17.287	38.554	kg	20.1	775	Hammond and Jones 2011
Aluminum	9.767	21.782	kg	155	3376	Hammond and Jones 2011
Copper	5.579	12.442	kg	42	523	Hammond and Jones 2011
Nickel	0.586	1.307	kg	164	214	Hammond and Jones 2008
Lead	0.588	1.311	kg	25.21	33	Hammond and Jones 2011
Chromium	0.488	1.088	kg	83	90	Hammond and Jones 2008
Zinc	0.276	0.616	kg	61.9	38	Hammond and Jones 2008
Tin	0.006	0.013	kg	250	3	Hammond and Jones 2008
PVC	0.028	0.062	kg	77.2	5	Hammond and Jones 2011
HDPE	1.438	3.207	kg	76.7	246	Hammond and Jones 2008 (UK)
R-134a refrigerant		2.450	kg	64	157	Campbell and McCulloch 1998
Manufacturing		1		1003	1003	Greening and Azapagic 2012
TOTAL for 1 system					**7729**	-
LC embodied energy (including replacements)					**22747**	-

CC ASHP 3 tons						
Real weight/Rey Martinez et al. weight			3.651			
Material	**# of units Rey Martinez**	**# of units Actual equipment**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Cast iron	14.625	53.399	kg	25	1335	Hammond and Jones 2011
Steel (low-alloy)	17.287	63.119	kg	20.1	1269	Hammond and Jones 2011
Aluminum	9.767	35.661	kg	155	5528	Hammond and Jones 2011
Copper	5.579	20.370	kg	42	856	Hammond and Jones 2011
Nickel	0.586	2.140	kg	164	351	Hammond and Jones 2008
Lead	0.588	2.147	kg	25.21	54	Hammond and Jones 2011
Chromium	0.488	1.782	kg	83	148	Hammond and Jones 2008
Zinc	0.276	1.008	kg	61.9	62	Hammond and Jones 2008
Tin	0.006	0.022	kg	250	5	Hammond and Jones 2008
PVC	0.028	0.102	kg	77.2	8	Hammond and Jones 2011
HDPE	1.438	5.250	kg	76.7	403	Hammond and Jones 2008
R-134a refrigerant		4.9	kg	64	314	Campbell and McCulloch 1998
Manufacturing	1			1644	1644	Greening and Azapagic 2012
TOTAL for 1 system					**11976**	-
LC embodied energy (including replacements)					**37424**	-

For the ground-source heat pump, a study from Greening and Azapagic is used, also with a weight ratio. Because the unit studied in this article is a water-to-water heat pump, materials for the fan and coil of heat pumps described by Rey Martínez et al. are added to the inventory. Materials for the ground loop are estimated by calculating the length and volume of the tubes.

GSHP 2 tons with ground loop						
Real weight/Greening and Azapagic weight			1.351			
Material	**# of units Greening**	**# of units Actual equipment**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Steel	95	128.311	kg	20.1	1910	Hammond and Jones 2011
Copper	22	29.714	kg	42	924	Hammond and Jones 2011
Elastomere	10	13.506	kg	101.7	1017	Hammond and Jones 2008
Polyolester oil	1.7	2.296	kg		0	N/A : neglected
PVC	1	1.351	kg	77.2	77	Hammond and Jones 2011
R-134a refrigerant	3.09	4.173	kg	64	198	Campbell and McCulloch 1998
Fan from Rey Martinez et al.	*Ratio*	*3.543*				-
Steel (low-alloy)	1.395	4.942	kg	20.1	28	Hammond and Jones 2011
Aluminum	2.61	9.246	kg	155	1433	Hammond and Jones 2011
Copper	0.14	0.496	kg	42	21	Hammond and Jones 2011
HDPE	0.329	1.166	kg	76.7	89	Hammond and Jones 2008
Zinc	0.026	0.092	kg	61.9	6	Hammond and Jones 2008
Manufacturing	1212	1636.975	MJ	1636.98	1637	Greening and Azapagic 2012
Ground-loop (89.3 m)	-	89.3	m			
Cross-linked polyethylene	-	13.78	kg	83.1	1145	Hammond and Jones 2008
Propylene glycol	-	60.55	kg	17	1029	Ardente et al. 2005
TOTAL for 1 system					**9494**	-
LC embodied energy (including replacements)					**21029**	-

The material inventory for DHW tanks and water storage tanks is estimated with dimension data provided by the manufacturers. Values for flat-plate collectors as well as for solar water heater accessories are taken from an article by Hernandez and Kenny (2012).

Solar water heater					
Size 1: 2x 4'x8' (5.95 m²), 1.6 gpm, tilt 30°, storage 60 U.S gal					
Material	**# of units**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Flat-plate collectors	5.95	m²	1640	9758	Hernandez and Kenny 2012
Solar storage tank	1	unit		2757	-
Glass	22.91	kg	15	344	Hammond and Jones 2011
Steel	68.46	kg	20.1	1376	Hammond and Jones 2011
Polyurethane	0.13	m³	4446	578	Petersdorff et al. 2003
Copper tubing	1		1400	1400	Hernandez and Kenny 2012
Expension vessel	1		300	300	Hernandez and Kenny 2012
Circulating pump	1		120	120	Hernandez and Kenny 2012
Glycol 50%	5.95	m²	100	595	Hernandez and Kenny 2012
TOTAL for 1 system				**14930**	
LC embodied energy (including replacements)				**48054**	

Solar system description	EE for 1 system (MJ)	Life cycle EE (MJ)
Size 1: 2x 4'x8' (5.95 m²), 1.6 gpm, tilt 30°, storage 75 U.S gal	15451	49355
Size 1: 2x 4'x8' (5.95 m²), 1.6 gpm, tilt 40°, storage 60 U.S gal	18650	55494
Size 1: 2x 4'x8' (5.95 m²), 1.6 gpm, tilt 40°, storage 75 U.S gal	19171	56795
Size 2: 2x 4'x10' (7.46m²), 2 gpm, tilt 30°, storage 60 U.S gal	17558	54516
Size 2: 2x 4'x10' (7.46m²), 2 gpm, tilt 30°, storage 75 U.S gal	18078	55818
Size 2: 2x 4'x10' (7.46m²), 2 gpm, tilt 40°, storage 60 U.S gal	21278	61956
Size 2: 2x 4'x10' (7.46m²), 2 gpm, tilt 40°, storage 75 U.S gal	21798	63258
Size 3: 3x 4'x8' (8.979 m²), 2.4 gpm, tilt 30°, storage 60 U.S gal	20202	61022
Size 3: 3x 4'x8' (8.979 m²), 2.4 gpm, tilt 30°, storage 75 U.S gal	20723	62324
Size 3: 3x 4'x8' (8.979 m²), 2.4 gpm, tilt 40°, storage 60 U.S gal	25782	72182
Size 3: 3x 4'x8' (8.979 m²), 2.4 gpm, tilt 40°, storage 75 U.S gal	26303	73484

Electric DHW tank					
Material	**# of units**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Steel	57.730	kg	20.1	1160	Hammond and Jones 2011
Glass	19.35	kg	15	290	Hammond and Jones 2011
Polyurethane	4.63	kg	125.2	580	Petersdorff et al. 2003
Magnesium	0.491	kg	366	180	Cherubini et al. 2008
Nickel	1.44	kg	164	236	Hammond and Jones 2008
Chromium	0.36	kg	83	30	Hammond and Jones 2008
TOTAL for 1 system				**2652**	-
LC embodied energy (including replacements)				**12055**	-

Desuperheater					
Material	**# of units**	**Units**	**EE (MJ) per unit**	**Total EE (MJ)**	**Source for embodied energy**
Copper	6.82	kg	42	286	Hammond and Jones 2011
TOTAL for 1 system				**286**	-
LC embodied energy (including replacements)				**651**	-

14. Appendix F: Detailed simulation results and LC analysis for mechanical systems with the min. LCC envelope

Electric furnace with central air conditioning

Life cycle energy

Annual operating energy for electric furnace with central AC

Heating energy delivered	7104 kWh
Heating electricity consumed	7104 kWh
Cooling energy delivered	688 kWh
Cooling electricity consumed	149 kWh
Total electricity consumed	7253 kWh
Total operating primary energy consumed	9395 kWh

Life cycle energy for electric furnace with central AC

Embodied energy for one replacement of furnace with AC unit	2,298 kWh (8,276 MJ)
Total life cycle embodied energy	7,663 kWh (27,588 MJ)
Total primary operating energy	469,741 kWh (1,691,068 MJ)
Total primary life cycle energy	477,404 kWh (1,718,653 MJ)

Life cycle cost

Life cycle cost for electric furnace with central AC

Investment cost – Electric heating element	$342
Investment cost - Central air conditioning	$5582
Life cycle material cost	$14,619
Annual energy cost (for year 1)	$568.64
Total operating cost (for 50 years)	$40,713
Total life cycle cost	$55,578

Air-source heat pump

Life cycle energy

Annual operating energy for air-source heat pump

Heating energy delivered	6892 kWh
Heating electricity consumed by heat pump	1312 kWh
Heating electricity consumed by reheat element	1195 kWh
Heating electricity consumed by auxiliary element	1969 kWh
Cooling energy delivered	737 kWh
Cooling electricity consumed	138 kWh
Total electricity consumed	4614 kWh
Total operating primary energy consumed	5977 kWh

Life cycle energy for air-source heat pump

Embodied energy for one replacement of air-source heat pump	2,022 kWh (7279 MJ)
Total life cycle embodied energy	6,319 kWh (22,747 MJ)
Total primary operating energy	298,850 kWh (1,075,860 MJ)
Total primary life cycle energy	305,169 kWh (1,098,608 MJ)

Life cycle cost

Life cycle cost for air-source heat pump

Investment cost	$6,836
Life cycle material cost	$19,189
Annual operation energy cost (for year 1)	$361.74
Total operation energy cost (for 50 years)	$25,900
Total life cycle cost	$45,089

Cold-climate air-source heat pump

Life cycle energy

Annual operating energy for cold-climate air-source heat pump

Heating energy delivered	6,766 kWh
Heating electricity consumed by heat pump	2,390 kWh
Heating electricity consumed by reheat element	1,472 kWh
Heating electricity consumed by auxiliary element	0 kWh
Cooling energy delivered	841 kWh
Cooling electricity consumed	177 kWh
Total electricity consumed	4,039 kWh
Total operating primary energy consumed	5,232 kWh

Life cycle energy for cold-climate air-source heat pump

Embodied energy for one replacement of cold-climate air-source heat pump	3,327 kWh (11976 MJ)
Total life cycle embodied energy	10,396 kWh (37,424 MJ)
Total primary operating energy	261,600 kWh (941,760 MJ)
Total primary life cycle energy	271,996 kWh (979,184 MJ)

Life cycle cost

Life cycle cost for cold-climate air-source heat pump

Investment cost	$9,114
Life cycle material cost	$25,585
Annual energy cost (for year 1)	$316.65
Total operating cost (for 50 years)	$22,672
Total life cycle cost	$48,258

Ground-source water-to-air heat pump

Life cycle energy

Annual operating energy for ground-source heat pump

Heating energy delivered	6,962 kWh
Heating electricity consumed by heat pump	1,555 kWh
Heating electricity consumed by reheat element	1,108 kWh
Heating electricity consumed by auxiliary element	0 kWh
Cooling energy delivered	862 kWh
Cooling electricity consumed	107 kWh
Total electricity consumed	2,770 kWh
Total operating primary energy consumed	3,588 kWh

Life cycle energy for ground-source heat pump

Embodied energy for one replacement of ground-source heat pump with ground loop	2,643 kWh (9,514 MJ)
Total life cycle embodied energy	5,238 kWh (18,855 MJ)
Total primary operating energy	179,400 kWh (645,840 MJ)
Total primary life cycle energy	184,638 kWh (664,697 MJ)

Life cycle cost

Life cycle cost for ground-source heat pump

Investment cost - Ground-source heat pump	$8,544
Investment cost – Ground loop	$4,394
Life cycle material cost	$21,107
Annual energy cost (for year 1)	$217.17
Total operating cost (for 50 years)	$15,549
Total life cycle cost	$37,656

Electric domestic hot water tank

Life cycle energy

Annual operating energy for electric domestic hot water tank

Electricity consumption	4,578 kWh
Total operating primary energy consumed	5,930 kWh

Life cycle energy for electric domestic hot water tank

Embodied energy for one replacement of the electric domestic hot water tank	639 kWh (2299 MJ)
Total life cycle embodied energy	2,903 kWh (10,452 MJ)
Total primary operating energy	296,512 kWh (1,067,443 MJ)
Total primary life cycle energy	299,415 kWh (1,077,894 MJ)

Life cycle cost

Life cycle cost for electric domestic hot water tank (60 imp. gal)

Investment cost	$791
Life cycle material cost	$3,179
Annual energy cost (for year 1)	$358.92
Total operating energy cost	$25,698
Total life cycle cost	$28,876

Desuperheater with electrical back-up

Life cycle energy

Annual operating energy for desuperheater with electrical back-up

Electricity consumption of the DHW tank	3,935 kWh
Additional compressor electricity consumption	200 kWh
Additional pump electricity consumption	66 kWh
Electricity consumption	4,201 kWh
Total operating primary energy consumed	5,442 kWh

Life cycle energy for desuperheater with electrical back-up

Embodied energy for one replacement of the desuperheater and electric domestic hot water tank	718 kWh (2,585 MJ)
Total life cycle embodied energy	3,554 kWh (12,794 MJ)
Total primary operating energy	272,078 kWh (979,480 MJ)
Total primary life cycle energy	275,632 kWh (992,275 MJ)

Life cycle cost

Life cycle cost for desuperheater with electrical back-up

Investment cost – Electric DHW tank	\$791
Investment cost – Desuperheater	\$684
Life cycle material cost	\$3,179
Annual energy cost (for year 1)	\$329.36
Total operating energy cost	\$23,582
Total life cycle cost	\$28,314

Annual operating energy for solar water heater with electrical back-up

Electricity consumption of the DHW tank	2,554 kWh
Additional pump electricity consumption	82 kWh
Solar fraction	0.411
Electricity consumption	2,636 kWh
Total operating primary energy consumed	3,414 kWh

Life cycle energy for solar water heater with electrical back-up

Embodied energy for one replacement of the solar water heater with electrical back-up system	4,292 kWh (15,451 MJ)
Total life cycle embodied energy	13,710 kWh (49,355 MJ)
Total primary operating energy	170,700 kWh (614,520 MJ)
Total primary life cycle energy	184,410 kWh (663,876 MJ)

Life cycle cost

Life cycle cost for solar water heater with electrical back-up

Investment cost – Electric DHW tank	\$791
Investment cost – Solar water heating system	\$7,887
Life cycle material cost	\$19,787
Annual energy cost (for year 1)	\$206.66
Total operating energy cost	\$14,797
Total life cycle cost	\$34,584