Multi-objective life cycle optimization of a single-family house envelope

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Abstract

This paper presents the optimization of a single-family house envelope, using two objective functions, the life cycle primary energy use (LCE) and cost (LCC). The methodology is applied to a proposed design of a house from a modular housing company. A dynamic simulation model is created in TRNSYS, to simulate the annual heating and cooling energy consumption for the climate of Ste-Agathe-des-Monts, Québec. The Particle Swarm Optimization algorithm available in GenOpt optimization software is used.

The results show that the optimum insulation level, obtained either from the life cycle energy use or the life cycle cost, is greater than those values recommended by the energy efficient building regulation in Quebec. A high potential for improvement of the initial design of the house is found when compared to the optimum solutions.

1 Introduction

In the past decades, several programs have been introduced to improve the energy efficiency of new residential buildings in Canada. The Novo-Climat houses (Agence de l'efficacité énergétique 2011) in Quebec are one example, as they are well known by the population and represent an improvement over the current practice. More advanced programs, such as the Canada Mortgage and House Corporation's EQuilibrium housing demonstration project (Canada Mortgage and Housing Corporation 2009), have proven the feasibility of designing and building houses with lower energy consumption in cold climates. However, most of these programs are primarily based on annual energy consumption targets and do not take into account the other impacts of the building in its lifespan. While some homeowners and builders would like to design their houses to diminish their cost and environmental impacts over their entire lifespan, there is a lack of information on how to design Canadian residential buildings that minimize both the life cycle energy use (LCE) and life cycle cost (LCC).

Life cycle analysis of building envelopes has been a subject of interest for many years amongst the scientific community, and previous work has proven its relevance in the design of sustainable buildings. 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 2010). For those reasons, it is necessary to include life cycle analysis in the optimization process for high performance buildings.

A few articles have evaluated building envelope from a life cycle point of view. Baouendi et al. (2005) proposed an integrated tool for assessing life cycle energy use, emission and cost for exterior envelopes of Canadian houses. Some authors have applied multi-objective optimization to envelope design in order to account for the necessary trade-offs between costs and impacts. Wang et al. (2005) used life cycle cost and life cycle exergy consumption as criteria for an office building in Montreal, while Verbeeck & Hens (2007) minimized life cycle cost, life cycle non-renewable energy consumption and life cycle global warming potential for both the envelope and HVAC systems in Belgian climate. Various research projects had the objective of minimizing life cycle cost for the envelope design (Hasan et al. 2008, Tuhus-Dubrow & Krarti 2010, Bichiou & Krarti 2011). Roos & Gorgolewski (2011) conducted a multi-criteria assessment of wood-frame walls typical of Canadian construction methods, while Folvik et al. (2011) analyzed the environmental payback of very thick insulation in Finland climate.

However, some researchers have pointed out that each case is very specific to its location and that there is a need for more case studies. Indeed, energy prices, initial cost of available construction materials and the associated labor, as well as climate, have a considerable impact on the results. Consequently, this work presents the optimization of a single-family house envelope using two objective functions, the life cycle energy use and cost. To the best knowledge of the authors, no other research applied to Canadian conditions has been conducted on the comprehensive optimization of building envelope using these two objective functions. Life cycle energy use is selected as a criterion because of its major impact on environment, namely on resource depletion and eutrophication (Itard 2007).

2 Methodology

Building model

A base case house, as designed by a modular housing company based in Montréal, is first modeled using TRNSYS 16 (Solar Energy Laboratory 2006). The 130 m² house has a full basement, a ground floor and a mezzanine, and is represented as a multi-zone building (Type56) in the TRNSYS environment. Other components are added to the model, namely: a detailed ground model (Type701), differential controllers as thermostats (Type2), heat recovery ventilator (Type760) and overhangs (Type34). The weather data file used is for Ste-Agathe-des-Monts, a town located approximately 100 km north-west of Montreal, where the actual modeled house will be built. Table 1 presents the main house parameters which are kept constant through optimization.

Table 1: Constant house parameters

Parameter	*Value*
Floor area	130 m²
Total envelope area (above ground)	313 m²
Air infiltration rate at 50 Pa	1 ACH
Day heating setpoint	21°C
Night heating setpoint	18°C
Cooling setpoint	24°C
Mechanical ventilation rate	50 L/s
Window centre-of-glass U-value	0.7 W/m².K
Window area on east and west facades (each)	6 m²

Optimization variables are selected to represent the actual construction of wall assemblies in Canada. Consequently, cavity insulation and outside insulation are optimized separately, and up to two layers of different insulation materials can be used for the roof insulation. Wall insulation is characterized by two variables: thickness and material type. This approach allows for a proper assessment of not only the transient heat transfer through the wall, but also of the price, embodied energy and volume occupied by each type of insulation materials. Special care was taken to select a variety of materials widely available on the Canadian market. Wood framing of walls is adjusted to allow the specified thickness of insulation to fit in the cavity, respecting standard wood stud sizes (90 mm/3.5 in, 140 mm/5.5 in, 190 mm/7.5 in or double 90 mm/3.5 in studs). The range of values for the optimization variables reflects the practical limitations that are faced by the developer in terms of dimensions, transportation restrictions, and local costs. Transportation is a major consideration in this project because the house is to be built in modules and then be transported to the construction site; the thickness of the roof is therefore limited by the maximum possible height of the module. Also, to fit the contemporaneous architectural style that was intended for the building, the roof is flat. To limit thermal bridging, a 38 mm layer of sprayed polyurethane is applied on the outside of the roof structure; this layer is constant for all configurations. The minimal insulation values are selected to comply with the *Regulation respecting energy conservation in new buildings* (Government of Québec 1992). The list of optimization variables, which are all discrete variables, and the corresponding available options and range of dimensions are given in Table 2.

Table 2: Optimization variables

Item	*Variable*	*Available options and dimensions*
1	Insulation material – wall cavity	Sprayed polyurethane, fiberglass batt, mineral fiber, blown cellulose, foil-faced polyisocyanurate
2	Insulation material - outside of wall studs	Sprayed polyurethane, extruded polystyrene
3	Insulation thickness – wall cavity	[75 – 250] mm Increment: 25 mm
4	Insulation thickness – outside of wall studs	[25 – 100] mm Increment: 25 mm
5	First insulation material for roof cavity (towards outside of roof)	Sprayed polyurethane, foil-faced polyisocyanurate
6	Second insulation material for roof cavity	Fiberglass batt, mineral fiber, blown cellulose
7	Total roof insulation thickness	[150 – 225] mm Increment: 25 mm
8	Ratio of first insulation material thickness to total insulation thickness	[0-1] Increment: 0.2
9	Insulation location and material for the foundation walls	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	[75 -175]mm Increment: 25 mm
11	Basement floor insulation material	Sprayed polyurethane, extruded polystyrene
12	Basement floor insulation thickness	[25-100] mm Increment: 25mm
13	Flooring (above ground floors)	50 mm concrete, 100 mm concrete, hardwood
14	Area of south-facing windows	[10 – 46] m^2 Increment: 4 m^2

Because thermal bridges can cause as much as a 50 percent increase in nominal thermal transmittance of walls (Roos & Gorgolewski 2011), they are modelled in TRNSYS 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. For double-stud framing, the framing factor is 0.40, as studs are staggered and twice as numerous for a given wall area; the thermal bridge portion of this wall type is modelled with a combination of insulation and the wood stud to accurately represent the wall section. 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.

Life cycle cost and energy

The TRNSYS simulation returns the annual heating and cooling energy consumption, considering 100 percent efficiency for heating (baseboard heating) and a coefficient of performance of 3 for cooling (central air conditioning). It was decided to exclude energy consumption for domestic hot water and other electrical loads since they are not of importance for the optimization of the envelope. Site energy use is then converted to primary energy using a primary energy factor of 1.2953, as calculated for the energy mix of Québec in 2007 (Statistics Canada 2009). Life cycle primary energy use for materials is obtained mostly from the Athena Impact Estimator (Athena Sustainable Materials Institute 2008). For materials that are not available in this database, other sources from the scientific literature were used; Table 3 presents a sample of embodied energy data and references. Most cost data comes from RS Means Residential Cost Data 2011 (RS Means 2010). Prices for insulation were taken from estimates and price lists available from the modular housing company, since this data can greatly affect the optimization results.

Table 3: Sample of embodied primary energy data

Material	*Primary energy (MJ/m³)*	*Source*
Fiberglass batt	548	Athena SMI 2008
Blown cellulose	60	Athena SMI 2008
Extruded polystyrene	2918	Athena SMI 2008
Mineral wool	1080	Athena SMI 2008
Sprayed polyurethane	4446	Petersdorff 2002
Polyisocyanurate	2441	Athena SMI 2008
Lightweight concrete	1309	Hammond and Jones 2008

The life cycle analysis is conducted over a period of 50 years. 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 were based on 30 years, 80 years or annualized values. Also, while the Model National Energy Code of Canada for Houses (MNECH, Canadian Commission on Buildings and Fire Codes 1997) uses a timeframe of 30 years, it also points out that "it can be argued that [the numbers of year considered] should be the life of the building, which might exceeds 100 years." For both cost and energy use, maintenance replacements of materials are accounted for, including for example replacement of windows after 25 years and repainting of interior walls every 8 years. Life cycle energy is calculated using equation 1, where $E_{embodied}$ is the life cycle energy for all materials used in the production and maintenance of the house, and E_{op} is the annual heating and cooling energy consumption multiplied by the primary energy factor previously defined.

$$LCE = \sum E_{embodied} + 50 \cdot E_{op} \tag{1}$$

For life cycle cost calculations, the nominal discount rate is equal to 2.69%, the average interest rate for the period between 2001 and 2011 (Bank of Canada, 2011b), and an inflation rate of 2.03%, also equal to the average for Canada during this period (Bank of Canada, 2011a). The present value for total life cycle cost (LCC) for each design alternative is calculated using equation 2, where $C_{investment}$ is the building investment cost, $C_{M\&R}$ is the sum of discounted maintenance and replacement costs and C_{energy} is the discounted cost of energy over the study period of 50 years.

$$LCC = C_{investment} + C_{M\&R} + C_{energy} \tag{2}$$

Optimization algorithm

GenOpt 3.0.3 (Lawrence Berkeley National Laboratory, 2010) is a program that optimizes a set of variables to minimize one given objective function calculated by a simulation software. An optimization algorithm is selected by the user from a bank of available algorithms. The simulation software must read text input and write text output in order to be compatible with GenOpt.

For each iteration of the optimization algorithm, GenOpt sets the value of all the independent variables (outlined in Table 2). As each wall is defined as an assembly of material layers, GenOpt also calculates the thickness value for each insulation material layer, which can in turn be used by TRNSYS to define wall compositions. TRNSYS then calculates the operating energy use for heating and cooling corresponding to each envelope case, as well as the embodied energy and the cost for the whole house. Life cycle cost and energy is included in TRNSYS in the form of equation blocks, where the variables are linked to the values defined in GenOpt. Figure 1 details the interactions between GenOpt and TRNSYS in the form of a flow chart.

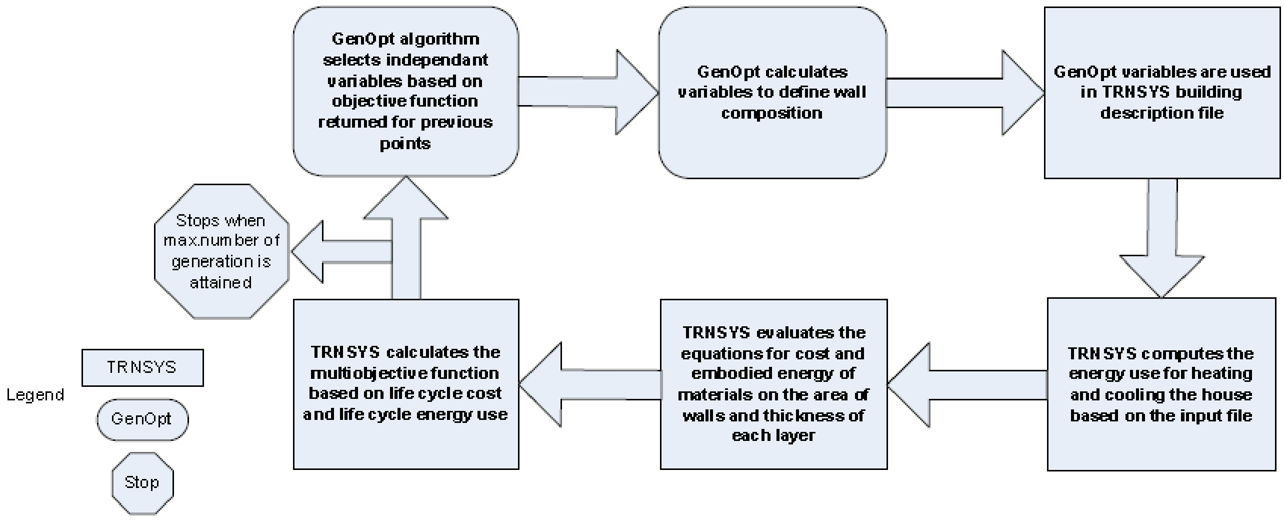

Figure 1: Flowchart of interaction between TRNSYS and GenOpt

A Particle Swarm Optimization (PSO) algorithm is chosen from GenOpt library. Bichiou & Krarti (2011) have previously demonstrated the effectiveness of this algorithm in reducing the required computation time for a similar envelope optimization problem. That study also showed that the minimum found by the PSO algorithm was only slightly greater than the ones found by more computationally expensive algorithms (such as Sequential Search). It is also the recommended algorithm for discrete variables optimization with the GenOpt program (Wetter 2009).

Experts make different recommendations when it comes to selecting a population size and a maximum number of generations. As summarized by Wetter (2009): Parsapoulos & 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 & Engelbrecht (suggest a population size greater than 20 with 2000 to 5000 generations, while Kennedy & 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.

The studies summarized by Wetter (2009) also suggest values for other algorithm parameters. Table 4 lists the selected values for the Particle Swarm Optimization algorithm based on those articles and on Carlisle & Dozier (2001) as well as Kennedy& Mendes (2002).

Table 4: PSO algorithm parameters

PSO algorithm version	Inertia weight
Neighbourhood typology	Von Neumann
Cognitive acceleration constant	2.5
Social acceleration constant	1.5
Max velocity gain continuous	0
Max velocity gain discrete	4

Formulation of the objective function

One approach that is often used for multi-objective optimization, other than finding the Pareto front, is to merge all objective functions into one global objective function by using the weighting factors method (Hauglustaine & Azar Lema 2001, Kassab 2002, Alanne et al. 2007). In this study, we first minimized the life cycle cost and calculated the corresponding life cycle energy use, and then minimized the life cycle energy use and calculated the corresponding life cycle cost. 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 3. In each case, the sum of w_1 and w_2 is 1.

$$F = w_1 \frac{LCC - LCC_{max}}{LCC_{max} - LCC_{min}} + w_2 \frac{LCE - LCE_{max}}{LCE_{max} - LCE_{min}} \tag{3}$$

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.

3 Results and discussion

Optimal configurations

Table 5 presents the objective function values as well as the properties of the optimal envelope for three different objective functions (as defined in equation 3), as found by the PSO algorithm.

Table 5: 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 m².K/W	7.51 m².K/W	6.91m².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 m².K/W	11.08 m².K/W	8.67 m².K/W
Basement wall insulation	100 mm polyisocyanurate	175 mm polyisocyanurate	175 mm polyuisocyanurate
Basement wall effective thermal resistance	6.54 m².K/W	10.48 m².K/W	10.48 m².K/W
Basement floor insulation	100 mm extruded polystyrene	100 mm polyurethane	100 mm extruded polystyrene
Basement floor effective thermal resistance	3.57 m².K/W	4.05 m².K/W	3.57 m².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 m²	10 m²	10 m²

While Table 5 gives an overview of the characteristics of a low life cycle energy use or cost single-family house envelope, many other configurations yield similar results for each criterion. When analyzing the results file, the properties of all configurations which had an objective function within one percent of the optimal value are compared in order to obtain general design guidelines.

For LCC, 368 configurations return a value within 1% of the minimum (i.e. below $248,609) and 103 configurations yield a LCE value within 1% of the minimum (i.e.,below 1,510,153 MJ). For the w1=0.5 objective function, each criteria was allowed to vary within 1%, yielding a maximum objective function value of 0.8626. Table 6 presents the properties that are shared by more than 90% of envelope configurations within 1% of the optimum for each objective function.

Table 6: General design guide lines 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 outside of studs insulation thickness	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 m²	10-18 m²	10 m²

Table 6 also highlights the major differences and similarities between life cycle cost and life cycle energy minimization. It appears that the most important difference is the required thermal resistance for outside walls: LCC optimization leads to smaller thickness and the use of fibreglass batts for cavity insulation, while LCE optimization requires maximum thickness of cellulose considered in this study with double-stud walls as well as maximum outside studs insulation. The proportion of polyisocyanurate is also higher in the roof cavity when minimizing LCE. 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 are 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. This 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.

Design applications

Figure 2 shows the position of optimal solutions on a LCC vs. LCE Cartesian graph, with comparison to the initial design. The initial design was suggested with the idea of reducing energy consumption below Novo-Climat program requirements, using common building techniques and materials, but with no intent of optimizing energy or cost on a life cycle basis. In this base case, the roof cavity is insulated with 225 mm of sprayed polyurethane, and the exterior walls are insulated with 138 mm of blown cellulose and 25 mm of sprayed polyurethane outside studs. The basement floor is insulated with 50 mm of sprayed polyurethane, and the basement walls, with 75 mm of that same material.

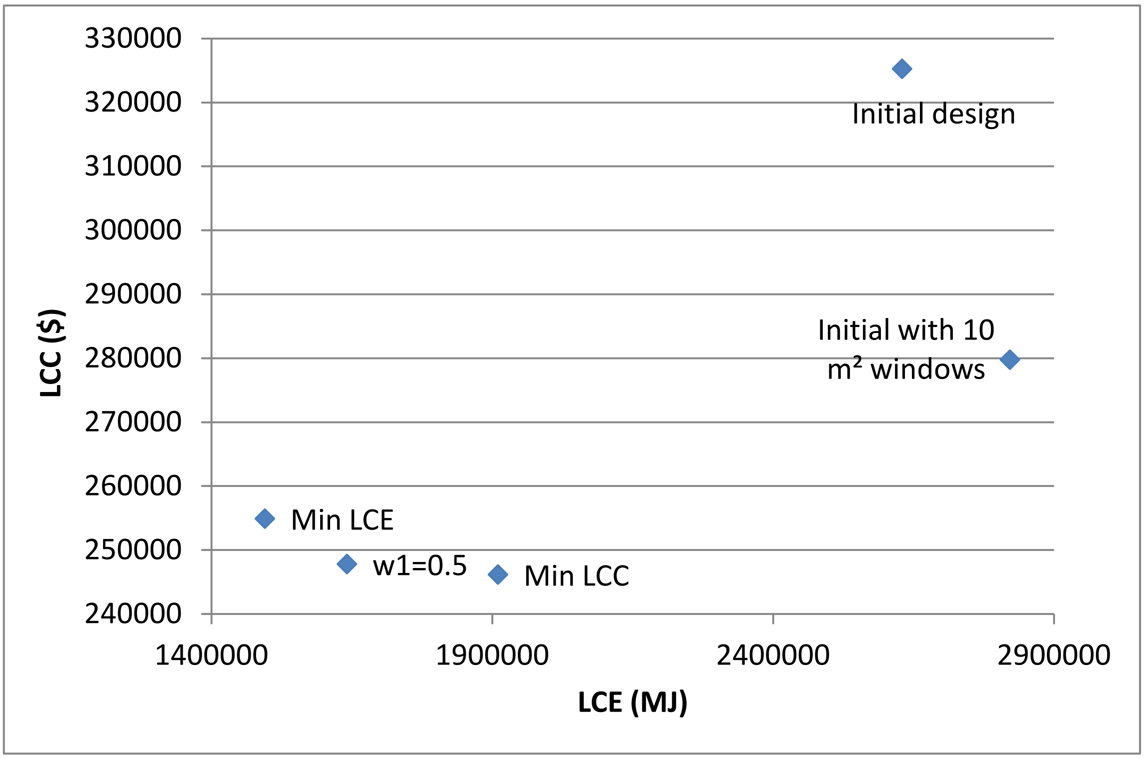

Figure 2: Optimal solutions and initial design

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 costs $1685.49. 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 file 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 criteria.

Comments

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 with codes and regulations from Canada is given in Table 7. In this table, the effective thermal resistances for Québec regulations and Novo-Climat are obtained 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 and that a new version is expected sometimes in 2012.

Table 7 : Comparison of effective thermal resistance values for minimum LCC with codes and regulations

	Québec regulations	*Novo-climat*	*MNECCH 1997*	*Min. LCC*
Walls (m².K/W)	2.32	2.53	4.1	6.88
Roof (m².K/W)	3.75	4.28	5.2	5.44
Basement walls (m².K/W)	1.51	1.77	3.1	6.54
Basement floor (m².K/W)	-	0.88	1.08	3.57

These differences 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. Another optimization run for LCC was conducted to assess the impact of the chosen electricity cost escalation rate on the results. While the minimum LCC decreased to $232,958 in comparison with the initial $246,149, the optimal configuration remained the same. The general guidelines for configurations within 1% of the objective function also remained essentially the same. All values used in this economical analysis seem reasonable to the authors, but their variation in the future remains uncertain.

While the results obtained for the envelope are optimal, they are limited to the envelope for a simple HVAC system. 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. This issue would be the subject of future work.

4 Conclusions

This work presented the life cycle cost and life cycle energy optimization of a single-family house envelope for a Québec climate, using a combination of the TRNSYS energy simulation software and GenOpt optimization software. The results demonstrated that higher levels of insulation than those suggested by energy efficiency codes or programs such as the MNECCH or Novo-climat are desirable, both from a life cycle energy and cost perspectives. The results, when compared to what is considered as a common energy efficient house, show that there is much room for improvement in our architectural practices.

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