A Comparative Assessment of Insulated Concrete Wall Technologies and Wood-frame Walls in Residential Buildings: A Multi-Criteria Analysis of Hygrothermal Performance, Cost, and Environmental Footprints

Aliakbar Jafarpour

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By: **Aliakbar Jafarpour**

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Signed by the final Examining Committee:

________________________ Dr. Hua Ge, Chair

________________________ Dr. Fuzhan Nasiri, Supervisor

________________________ Dr. Jeremy Clark, Examiner External (to program)

________________________ Dr. Sang Hyeok Han, Examiner

________________________ Dr. Hua Ge, Examiner

Approved by ____
Dr. F. Haghighat, GPD,
Department of Building, Civil and Environmental Engineering

____
Dr. Amir Asif, Dean
Faculty of Engineering and Computer Science

Date __________________________

ABSTRACT

A Comparative Assessment of Insulated Concrete Wall Technologies and Wood-frame Walls in Residential Buildings: A Multi-Criteria Analysis of Hygrothermal performance, Cost, and Environmental Footprints

Aliakbar Jafarpour

Utilizing appropriate materials and assemblies in building envelope components could lead to energy savings, increased durability, and sustainability gains. This study aims at providing an integrated assessment framework to compare three different types of exterior wall systems: wood frame, insulated concrete forms (ICFs), and pre-cast insulated concrete panel (PICP). The focus will be on assessing the building envelope performance, cost efficiency, and environmental impacts of these technologies. Such an assessment will influence the decisions on design characteristics of exterior walls as well as the selection of required materials. In doing so, first, the exterior wall technologies will be compared in terms of hygrothermal performance according to ASHREA standards and other relevant literature. Then, a life cost analysis is conducted in order to establish the cost profile of each technology in buildings including capital costs as well as space heating costs over their service life. Finally, we will turn to assessing the environmental footprints of each technology and its components through life cycle assessment (LCA) using Simapro software. The proposed framework incorporates multiple performance assessment criteria including well-being aspects, hygrothermal performance, life cycle assessment (LCA), and life cycle cost (LCC). Using these criteria, a decision making framework is developed to compare and rank the alternative exterior wall technologies, identifying the one that is best suited to particular case study buildings.

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Nomenclature

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CED	Centre for Environment and Development
EPS	Expanded Polystyrene
GHG	Green House Gas
HVAC	Heating, Ventilation and Air Conditioning
ICFs	Insulated Concrete Forms
LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCIA	Life Cycle Inventory Assessment
MCDM	Multi-Criteria Decision Making
NBC	National Building Cod of Canada
NZEH	Net Zero Energy Houses
RH	Relative Humidity
RSI	Thermal resistance or material in SI system (m^2.K/W)
R-Value	Thermal resistance or material in US system (ft^2. ^{o}F/Btu.in)
SHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineering
PICP	Pre-cast Insulated Concrete Panel
PUR	Polyurethane
WC	A single house with Wood-frame walls and Concrete structure
WW	A single house with Wood-frame walls and structure
ZEBs	Zero Energy Buildings

1 Introduction

There has been a growing interest in ZEBs (zero energy buildings) over the last several decades mainly focused on reducing space thermal loads in buildings and the incorporation of building integrated renewable energy technologies [1]. These kinds of thermal load reduction approaches using so-called passive building strategies could be achieved through the use of proper insulating materials, airtight assemblies, less thermal bridging and increasing the thermal mass of the building envelope [2] and [3]. In cold climate regions such as Canada, space heating energy demand accounts for approximately 60% of total annual energy consumption in residential buildings [4]. In this sense, heat loss reduction through building envelope components could lead to energy efficiency gains [5].

The results of space thermal load reduction would include economic benefits due to the lowering of utility costs as well as environmental benefits due to a notable decrease on overall energy demand for space heating/cooling. Energy provision requires more environmental degradation, resource depletion, and pollution emission. In this regard, there is a growing interest among practitioners, designers, and others involved in energy efficient building design to implement passive building strategies, for instance, LEED and BREEAM, which take into account energy efficiency on their evaluation criteria [6]. In Canada, there are two main initiatives to decrease energy consumptions in building include: Advanced House Program and Net-Zero Energy Home Coalition. The former was introduced by Natural Recourses Canada in 1990s [7] . And also, the latter one emphasizes on applying NZEHs for new Canadian home by 2030 [8]. In addition, ASHRAE released ASHRAE Advanced Energy Design Guides [9] along with recommendations for several building types in order to reach a goal of 30% reduction by considering traditional approach in design stage on energy consumption in new construction in contrast to ASHRAE 90.1-1999. Therefore, sustainability in buildings could be achieved via passive building strategies to making it both economically efficient as well as environmentally friendly.

Additionally, building envelope components such as roof, exterior walls, windows, exterior doors, and slab-on-grade play a crucial role in achieving energy efficient buildings. Furthermore, it is obvious that exterior walls can be considered a main part of the building envelope for three reasons; first, they interface with other building elements including fenestrations, roof, floor, foundation, and slab-on-grade as a system [10], [11], and [12]. Second, the window to wall ratio is a key factor in gaining desirable natural light, however, optimizing heat loss through glazing part by considering the efficient window to wall ratio where window often has lowest R-value could lead to energy efficiency [13]. Lastly, exterior walls should control moisture as well as condensation which usually occur on wall surface elements [14] and [15].

1.1 Problem statement

This study focuses on use of concrete wall technologies in Canada where most of the below grade stories are constructed with concrete walls because of their durability, resistance against heat and moisture transfers [16]. In this case, these types of concrete walls can be used as the above grade walls in buildings. Therefore, utilizing insulated concrete forms (ICFs) and pre-cast insulated concrete panel (PICP) wall technologies in exterior walls in comparison with conventional wood-frame walls could be considered as an efficient approach in order to achieve thermal load reduction in buildings as these walls have higher thermal mass, less thermal bridging, and lower permeability on air and vapor transmission [17] and [18]. Figure 1 illustrates the components of such walls; plotted via Auto CAD 2014 student version. In this sense, this study is to develop a decision making framework for ranking and selection of the alternative exterior walls for a typical residential building considering economic, well-being, environmental, and hygrothermal criteria.

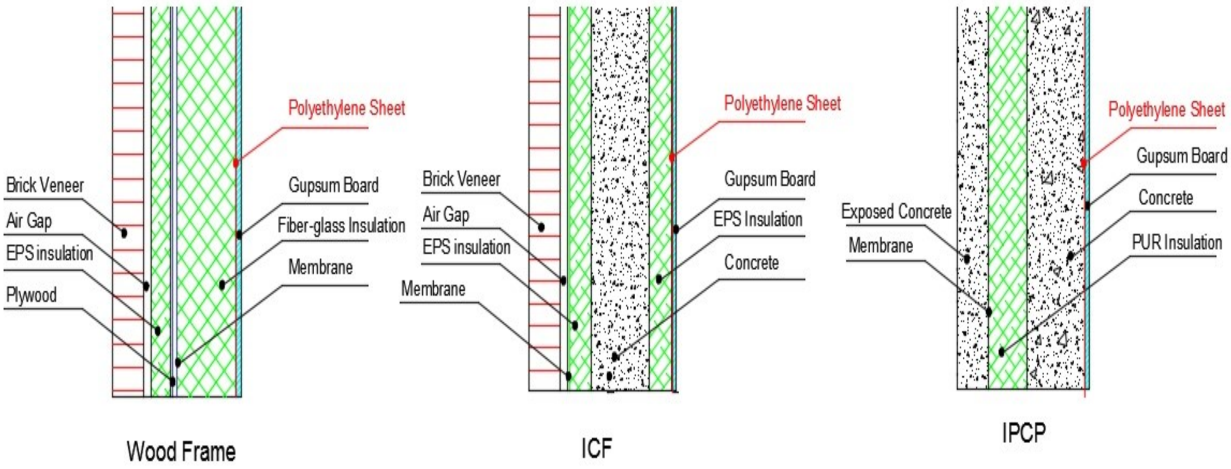


Figure 1 detail of three alternative exterior walls.

1.2 Research objectives

In the early stages of building design, various exterior wall alternatives should be evaluated in terms of a variety of criteria including well-being aspects, hygrothermal performances, costing and environmental impacts [19]. This thesis aims at developing an integrated assessment framework in order to evaluate these four criteria (including hygrothermal performance, well-being, LCA, and LCC) for three exterior wall technologies such as wood frame, ICFs, and PICP. The PICP walls would be applicable in large scale house constructions that in this study it is just evaluated as an insulated concrete wall thechnology. Technically, the proposed assessment framework addresses objectives as diverse as green building design, green building materials selection, building durability, safety, thermal performance, and ultimately long-term energy efficiency during the operational phase in which all these aspects can contribute to sustainability in some forms. This framework is integrated via a multi-criteria decision-making process which employs the ANP method as many of those criteria have direct or indirect interaction with each other. For instance, a high level of R-value has a direct impact on energy saving which is associated with energy cost as well as emissions to air. Figure 2 shows an overview of this thesis evaluation starts from alternative walls and end with sensitivity analysis.

The main objective of this study is to introduce a framework on selecting the best wall among alternatives using an integrated approach by making a direct link between four main criteria including performance, cost, environmental footprints, and well-being aspects. To the best of our knowledge, no study combined all aspects together to determine direct link through evaluation on choosing the best choice by taking into consideration of all four criteria in an integrated framework via MCDM approaches that have interactions and feedbacks among criteria.

1.3 Organization of thesis

The rest of this study is organized as follows. The second section is devoted to related work and literature reviews, where these relevant studies are divided in four areas including hygrothermal analysis, LCC, LCA, and MCDM. These four subsections will cover exterior wall studies in building applications.

The Methodology is presented in the third section where all boundaries, approaches, and basic principles are described. It starts with hygrothermal performance analysis, followed by LCC, LCA and the proposed decision analysis approach. The third section addresses basic thermodynamic principles as well as heat and moisture transfer mechanisms, follows by life cycle costing factors, followed by environmental impact assessment approach along with environmental indicators such as total energy usage and global warming potential. Finally, the ANP method as a MCDM approach is explained in details.

The fourth section introduces the case study scenarios along with all calculations. Indeed, this section takes into consideration the comparison of four alternative typical houses (scenarios) in order to evaluate the application of alternative exterior walls. This portion focuses on calculations as well as computer simulations including hygrothermal performance analysis, estimating the entire cost and assessing environmental impacts. The section fourth ends with ANP analysis in order to rank all criteria as well as define which alternative is suitable in Montreal. The rationale behind choosing ANP as the decision analysis framework is the fact it accounts for interrelationships among the criteria.

Results and limitations are discussed in the fifth section. And finally, the sixth section concludes the thesis by explaining the summary and identifying some future research avenues.

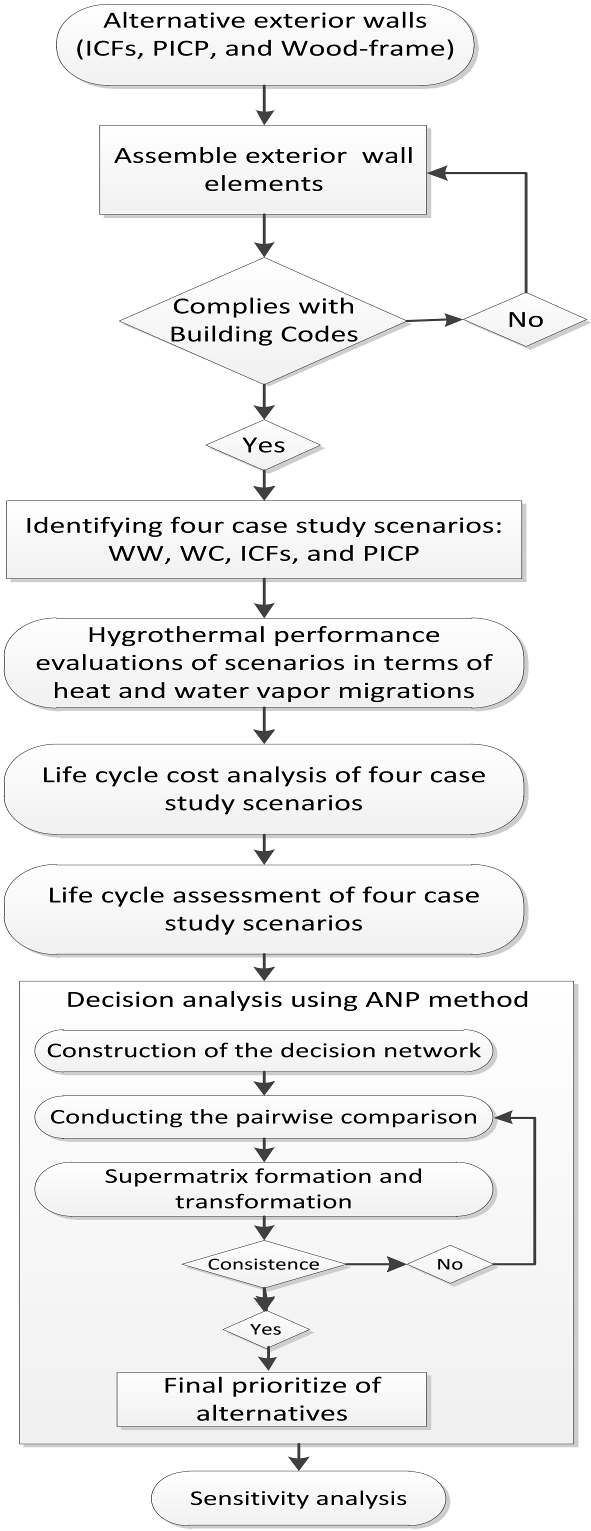


Figure 2 an overview of this study steps

2 Literature review

A comprehensive overview of literature on comparing wood and concrete applications as building materials can be summarized in two main areas: first, a comparison of wood and concrete where these alternatives are applied as a superstructure or mainframe in building and comparing them in terms of environmental impacts as well as cost of materials during pre-use, use phases and end-of-life [20]. The second area of study compared wood and concrete applications in other parts of building components such as exterior walls, roofs, and floors, assessing their consequences on sustainability, cost, energy efficiency and durability, safety and other relevant aspects. In this regard, there are a variety of publications that have compared exterior walls in buildings from their LCA, LCC, and hygrothermal perspectives, but they did not compare these three areas together in a single paper i.e. there is a scarcity of comparisons of exterior walls in terms of their performances, LCC, and LCA, in one specific study in order to provide a holistic assessment framework which would help practitioners make a decision based on a broad view covering all benefits and drawbacks. In this study, we cover these three areas in a case study (LCA, LCC, Hygrothermal) at a specific location, namely, Montreal. However well-being aspects were obtained based on survey questionnaires among experts. Consequently, the following literature reviews will focus on exterior wall in building applications.

2.1 Hygrothermal performance

In terms of hygrothermal performance, the NRCC (National Research Council Canada) [21] conducted a study on four types of exterior walls (stucco, EIFS, masonry wall, side-cladding and wood-frame) over two years for seven types of climates. In this report they collected data by using simulation with hygIRC (software) as well as field measurements of heat and moisture movement through these exterior walls. This study focused on how moisture leakage can be evaluated in exterior walls, although there is no specific conclusion showing which alternative acts more efficiently, Doebber et al. [17] compared different exterior wall technologies including ICFs, PCP (precast concrete panel), and improved wood-frame with a conventional wood-frame wall with their thermal performances in six different cities in the U.S. in a single family house. They applied COMIS software in order to model infiltration and determined the percentage of leakage through walls, windows and doors, and ceiling were around 34%, 7%, and 27%, respectively. The R-values for each alternative calculated was based on the "whole wall analysis method", in which they concluded that three main factors had significant impact on energy savings including thermal bridging control, a higher level of airtightness, and thermal mass. In addition, they found out by applying concrete wall technologies more energy efficient in terms of space heating and cooling. Among those technologies, ICFs had the highest energy saving levels. In 2001, Gajda et al. [22] modeled a single family house with DOE2 as energy simulation software for 11 types of exterior walls in

20 locations across the U.S. and five locations across Canada which were located at all ASHRAE location classifications. They focused on finding the annual energy consumption and cost in 25 identical houses with various exterior walls in which concrete mass, due to higher thermal mass capacity, had lower space heating and cooling costs. The orientation of the building with the same material could reduce between 6% and 52% on energy consumption. The energy consumption in seven real houses for a period of 11 months was measured [23] in Knoxville, STATE. They were simulated via DOE2.1E which houses were made of wood and ICF and it concluded that ICF consumes 7.5% less energy in these case studies as well as it is 10% more airtightness than conventional wood-frame. Both thermal transmittance (U-value) and thermal inertia were evaluated by Aset et al [24] in different exterior walls in order to find an optimum relationship between these two main factors. Therefore, they eventually concluded that to achieve a high performance wall, the R-value and thermal mass must be combined properly. They also observed that thermal mass reduced energy demand on space heating and cooling by nearly 10% and 20% respectively. Other studies such as [25], [26], [18], [27], [28], and [29] have evaluated hygrothermal performance of alternative exterior walls in buildings, especially those with different thermal mass, as well as various insulation thicknesses. Taking into account the different percentages, it is clear that thermal mass has a direct influence on energy efficiency by space thermal load demand reduction

NAHB Research Center conducted [30] a study in Chestertown, Md. in 1999 in three identical residential houses with different exterior walls (including ICFs plank system, ICFs block system, and wood-frame with fiber glasses insulation). They tested them on their space heating and cooling loads over two years after which they observed a 20% difference in annual energy consumption between ICFs houses and conventional wood-frames.

2.2 Life cycle assessment

The second type of studies focuses on environmental footprints assessments. In this sense, there are a variety of publications that have considered concrete and wood-frame walls as their case studies. Most of these evaluations concentrated on the following areas: first, heating or cooling energy consumption over use phase of building as well as primary energy. Second environmental impact of production and construction stages of building materials, and, lastly life cycle assessment of entire life so-called cradle-to-grave [31] and [32]. For instance, in Portugal two LCIA methods including CML 2001 (problem-oriented) and Eco-indicator 99 (damage-oriented) have been applied for seven exterior walls by Monteiro et al [33]. In 2011, a similar study [34] was carried out by this author on life cycle assessment of a house with alternative exterior walls where she applied three LCA methods: CED, CML 2001, and EI’99. The comparison of various exterior walls by considering different LCA methods showed that wood frame had less environmental impact in Portugal than other exterior walls. Another study [35] compared six types of exterior walls including concrete block, poured in-place concrete, insulated concrete, traditional wood frame, wood frame, and steel stud framing in the U.S. in which they applied ATHENA as a LCA software tool. The results determined that thermal mass has a significant role on energy saving in space cooling and heating over operation phase. Additionally, IFCs walls located in a hot climate zone had a high performance on energy saving in comparison with other alternatives which led to fewer impacts on energy and fossil fuel consumptions.

Portland Cement Association published a study [36] on wood frame and ICFs exterior walls in which a two-story house (over a 100-year life span) was modeled in five cities across the U.S. by applying the LCA approach via Simapro software [37]. The results showed that the production materials stage and construction phase were not the main category of environment degradation; in contrast, the majority consumption of fossil fuel occurred during the use phase. They concluded that the ICF house needed less energy on space heating or cooling, depending on climate. Therefore, applying ICF could have less negative impacts on the environment than wood frame. Dodoo et al [38] found that concrete houses need 3% less energy by applying the life cycle primary energy balance method. In this regard, Neethi Rajagopalan [39], in his PHD thesis (which assessed ICF and wood-frame via LCA method), found that over its entire life span, the ICF house would consume 20% less energy than wood-frame in Pittsburgh, Pennsylvania. Mantesi Eirini et al. [40] took the same approach as [39] did where the conclusion was a savings of 15% on space heating energy as compared to wood frame and, overall, a 10% savings annually on energy consumption. Consequently, many studies have applied the LCA method in order to evaluate the environmental impacts as well as total energy usage of buildings over their entire life span.

Despite all great values that LCA provides for building assessment in terms of environmental footprints, there are several limitations which were addressed by Chua et al. in 2015 [41]. They categorized them in four main areas of limitations of life cycle assessment as decision making support tools. These main areas include boundary scoping, methodology framework, data inventories, and practices. A brief explanation of limitations of each category provides as following according to their argument:

(1) Boundary scoping: It only focuses on environmental impacts, whereas some environmental qualities such as indoor air quality are not included in boundary scoping. Also, economic and social dimensions of sustainability are not included that they may affect the outcomes. Environmental impacts are assumed to be constant over time, while they will vary over long term run. Lastly, geographic site specific factors are not included.

(2) Methodology framework: As there are a variety of tools for LCA, thus different tools may include different types of impact categories that, in this sense, different studies may adopt different normalization factor, grouping or weighting methods. Moreover, there are many different studies that may have

different assumptions on building configurations, climate conditions, and other relevant aspects, where those assumptions in studies may lead to uncertainties.

(3) Data inventories: There are many materials or products from different manufactures that cannot be compared because of different methods in production. Furthermore, availability and uncertainty of inventory data can affect results.

(4) Practices: There are not sufficient benchmarks in LCA results and therefore life cycle evaluations of buildings are more complicated than conventional products. And also, designers and chain managers are reluctance in terms of their responsibilities towards LCA due to it adds more pressure to them in terms of avoiding certain products.

2.3 Life cycle cost

There are many studies that specifically analyzed the life cycle cost of residential or non-residential building. However, there are few studies that specifically evaluate life cycle cost of exterior walls, even though all above mentioned studies have analyzed the amount of energy and materials without mentioning their cost and economic assessments.

Hamidul Islam et al. [42] evaluated five types of exterior walls (including brick, autoclave aerated concrete block, fibro-cement sheet, pine saw logs and weatherboard) from LCC and LCA in Australian application. They came up with an optimization algorithm which evaluated these walls with AccuRate, a tool commonly used for operational energy performance in the Australian building industry. A cost effectiveness indicator (CEI) was proposed by [43] in China for cold climates. In this article two exterior walls were assessed with a basic non-insulated wall in order to measure the cost-effectiveness of exterior walls over their entire life span from raw material extraction, production, construction, operation and finally disposal costs. By adding proper insulation materials the consequences would be an overall drop of cost over the entire life span. Timi Mahli et al. [44] investigated the cost and GHG emissions by adding insulation and air gap in the exterior wall in Maldives. They concluded that there is an optimum level of insulation on the exterior wall that increases the construction cost which will save energy later over use phase as well as a 77% drop on GHG emissions. A similar study was carried out in Poland in 2011 [45] that compared the cost and environmental impacts of insulation thickness in different walls. A publication [46] analyzed ICFs application benefit in military building in the U.S. which showed that utilizing this material as exterior walls is not the most cost-effective material when constructing new facilities, however, it reduces energy demand on space heating and contributes towards total energy reduction goals which will have an economic benefit over the long-run.

Moving to drawbacks of life cycle cost analysis, there are several uncertainties in LCC analysis according to [47] that Hamidul Islam et al. reviewed many papers in LCC and found out that following limitations include: (1) By considering longer life span of a building, the inflation and discount rates would be less accurate. (2) Over time the prices of goods and services will vary that this will influence the accuracy of LCC results. (3) There is a various rate of prices of some building materials and more generally individual product in which this is not easy to predict, therefore we cannot say that LCC analysis is substantially accurate. (4) Thus, these uncertainties indicate that LCC analysis results in terms of estimating cost might not be as same as future cost.

2.4 Decision analysis

The application of a multi-criteria decision-making method has been observed in many articles and areas over the past three decades.

Table 1 summarizes several articles that have studied building envelope from decision analysis perspective. Practitioners have used a variety of MCDM methods in building design or construction, for instance, in 2014 Jato-Espino et al [48] published a review of the application of MCDM methods in construction that they summarized as23 different methods within 11 categories, most of which were analyzed using three main criteria: environmental, social and economic, in any construction work. They came up with a ranking of applications in which AHP was the highest one in this field. The same literature review has been done by Mela et al. [49] in building design which presented six well-known MCDM methods including VIRKOR, TOPSIS, PROMETHEE, PEG-Theorem, weighted sum method, and weighted product method. Eventually, they emphasized that the best method would be hard to define when considering a single family house as a case study to design and select the elements for that particular house. A passive house with five alternative exterior walls including brick, wood frame, solid wood, and aerated concrete was evaluated by K. Kuzman et al. [50] wherein they took into consideration two types of criteria including measurable criteria (end-of-life, emission of material, and functionality) and soft criteria (health aspects, psychological aspects, and aesthetics). AHP was utilized as a MCDM method that authors for pairwise comparison gathered data from 16 people including eight experts and eight dwellers who were living two in each one of the alternative houses. The gap in this paper is that they did not consider the relationship amongst the criteria (dependency) which could alter the results. In Turkey, Kabak et al. [51] evaluated three existing buildings (built in 1978, 2009, and 2001) based on BEP-TR which is an energy code in Turkey. They used the Fuzzy MCDM where the criteria were location, geometrical shape, building envelope, HVAC system, lighting, and renewable or cogeneration energy. Their goal was to find the building best matched to the BEP-TR. They applied nine expert judgments as their pairwise comparisons among criteria; however, they did not take into account the entire life cycle of these options in order to assess the consequences on long term operation.

Table 1 gaps in several decision analysis of building envelop in buildings

Method	Number of criteria	Case study	Author/year	Gaps
Combination of AHP and PROMETHEE	6	Five alternative main structures	Vahid Balali et al. 2014 [52]	PROMETHEE has more features than AHP but not covering all dependencies
DEMATEL, ANP, and ZOGP	4	Prefabrication or in-site constriction	Tsai 2012 [53]	Not evaluating entire life cycle
SAW, TOPSIS, GV, VS, VIKOR, and COPRAS, SWARA and TODIM	9	Five alternative insulation materials	Ginevicius et al 2008 [54]	Not considering inter-relationships and dependencies between criteria
SWARA and TODIM	5	Six identical houses with different exterior walls	Ruzgys et al. in 2014 [55]	Not considering inter-relationship and dependencies
AHP	6	5 passive houses with different exterior walls	K. Kuzman et al 2013 [50]	Not considering inter-relationships and dependencies between criteria
	3	Three types roof system in Tehran	Reza et al 2011 [56]	dependencies of criteria were not evaluated
	3	Comparing wood-frame and concrete in Vancouver	Hossaini et al. 2015 [57]	dependencies of criteria were not evaluated
Fuzzy MCDM (FANP)	7	three existing buildings built in 1978, 2009, and 2001 in Turkey	Kabak et al 2014 [51]	Case studies are not identical
MCDM	4	Three types of exterior walls	Turskis et al 2009 [58]	LEVI 4 software which not taking into account dependencies
	10	Five types of light wood frame walls in Quebec city	D. Frentte et al. 2008 [59]	There is not any MCDM analysis and left it as future work

In the other study, Reza et al. [56] assessed residential buildings, which MCDM was applied with AHP method to compare three types of roof systems in Tehran including concrete block, clay block, and EPS, taking into account three main criteria: environmental impact, economic, and social aspects. They concluded that EPS block was the best alternative in this city; however, the dependencies of criteria were not evaluated. In the area of construction management, a software called LEVI 4 was applied on MCDM for cost benefit analysis by Turskis et al. in 2009 [58]. They considered four alternative exterior walls as their case study with four main criteria including cost of square meter of walls, weight of wall per square meter, R-value, and durability. In a relevant study by Hossaini et al. [57] to compare wood frame and concrete frame building in Vancouver,, they focused on LCA by utilizing AHP method. Their case study was a six-story building made either with wood or concrete as a main structure. LCA, life cycle social impacts, and LCC were considered as the main criteria with 20 sub-criteria which were analyzed as independent criteria while in fact they have influence on each other. They concluded that wood frame is a more efficient alternative than concrete. Vahid Balali et al. [52] compared two methods, AHP and PROMETHEE, on decision-making for the selection of the building structural system. They had five alternative structural systems including LSF, 3D Panel, ICFs, Tunnel Framework, and Tronco, along with six main criteria including cost, ease of construction, energy saving, LCA, dead load, and number of floors. They determined that PROMETHEE has some unique features which are not available in AHP. Two construction methods, namely prefabrication method and conventional on-site method, were evaluated in 2012 by Tsai [53]. The method for MCDM was integrated with DEMATEL, ANP, and ZOGP methods, with criteria including resource conservation, energy efficiency, environmental quality, and cost reduction. This article showed that in some cases, combination of other MCDM methods could cover all criteria while obtaining a particular goal.

In order to evaluate wall insulation materials, five alternatives were selected in a study done by Ginevicius et al [54] taking into account nine criteria. They analyzed their study using six MCDM methods including SAW, TOPSIS, GV, VS, VIKOR, and COPRAS and they found that all these methods have the same peculiarities. In a similar study on exterior walls done in Lithuania by Ruzgys et al. in 2014 [55], they combined SWARA and TODIM methods as a MCDM method. The case studies here involved six identical residential buildings with different exterior wall insulations. The criteria that they relied on included cost of insulation, duration of work, payback period, energy losses, and water vapour diffusion. In another similar study on exterior walls, D. Frentte et al. [59] applied MCDM method for evaluating five types of light-frame wood walls in Quebec City, Canada. They considered two main criteria including first constraint criteria (such as in plane shear resistance, fire performance, R-value, air barrier, and water vapor retarder) and second performance criteria (moisture management, sound control, construction cost, maintenance cost, HVAC cost over 20 years, environmental impact). They did not use the MCDM method to evaluate their comparison in this article and they left it as a future work.

As observed from these studies on exterior walls or building envelopes, there is a growing interest towards applying the MCDM method on analyzing types of materials and technologies in building construction. These studies indicate that by having a goal, finding a solution among alternatives would be achievable via MCDM approaches. Overall, ANP would be a good match to our case study because of its features which are explained in methodology and 4.3.4 sections. The advantages of ANP method are explained as follows [60, 61]:

AHP makes decision making problems easy as a hierarchy in a top-to-down approach, however in many complicated decision problem AHP method is not able to solve the problem due to interdependent influences among criteria or alternatives. In these cases, ANP is highly recommended by many studies since this method takes into consideration dependencies and feedbacks this method was introduce by Saaty in 1996 [60]. In addition, the ANP structure looks like a network, where this network shows all interactions among elements. Based on these interactions the pairwise comparison is carried out between each two elements in order to create a super-matrix. The great advantage of ANP is that it can mix quantitative and qualitative factors into a decision in which makes it more flexible in terms of transparency of a modeling a decision making process [62]. In other words, ANP provides a systematic approach for decision-makers to deal with dependency and feedback. Therefore, in this thesis we apply ANP method because, first of all, it matches to our structures, and also ANP has this capability to take into account an actual relationship between two types of our criteria such as measurable or non-measurable. These types of tangible and non-tangible criteria were already explained in introduction.

3 Methodology

In this study, considering various areas of evaluation requires specific knowledge ranging from basic thermodynamic principles, economic, and environmental impact. Thus, there is a variety of areas focusing on exterior wall evaluation including hygrothermal performance, life cycle assessment (environmental footprints, life cycle cost, and MCDM analysis. In addition, for well-being aspects of our case studies, we take into consideration the experts' judgment through surveys. We do not address a specific methodology to evaluate the well-being aspects of our case studies in this section. These methodology descriptions are based on literature, standards, building codes, and simulation through the use of several software programs.

3.1 Hygrothermal performance analysis

The main role of the building envelope is to control environmental loads such as heat, air, and moisture (HAM) between the inside environment and the outside environment. In fact, in practice there is a combination of these environmental loads that needs to be controlled by designing a proper building envelope [63]. The hygrothermal performance methodology in this study only covers heat transfer due to conduction and water vapor diffusion. Therefore, these two mechanisms will be explained separately, although in reality, on a simulation stage, we take into account combinations of environmental loads.

In cold climate regions like Canada, the heat transfer (heat loss) in buildings could cause two main issues First, increasing energy demands for space heating, and, second, the influence on occupants' comfort. In order to minimize these effects, all elements in the building envelope should be designed and selected in order to prevent heat transfer. There are three heat transfer mechanisms: conduction, radiation, and convection. In this study, our analysis is on conduction as a main factor related to conductivity of building materials which are used in exterior walls. In this regard, Fourier's law (from ASHRAE handbook: fundamentals 2013 chapter 25) is applicable in a solid as following:

$$q = -k\ grad(t) = -(k_x \frac{dt}{dx} + k_y \frac{dt}{dy} k_z \frac{dt}{dz}) \tag{1}$$

It is assumed that materials of wall assembly are isotropic; the second assumption here is that heat transfers in one direction, therefore the heat flux will be as:

$$q = -k_m \frac{dt}{dx} = -\frac{1}{R}\ dt \tag{2}$$

Where, R is thermal resistance of layers with thickness of dx. This R associates with material properties. It can be obtained from table 1 of "ASHRAE handbook: fundamentals 2013" chapter 26. Moreover, there are various thermal resistance definitions which associated with how the thermal resistance is considered through assembly. The surface-to-surface thermal resistance of a wall assembly is in series that is called “R-value of system”. Taking into account film resistances of either sides of the wall, causes of combination of radiation and convection will add to the R-value of the system which is called “R-value of assembly”. These film resistance coefficients can be obtained from ASHRAE, however, based on the ASHRAE recommendation we consider R_o and R_i equal to 0.03 and 0.12 (m^2K/W) for outside and inside surface in winter, respectively. Thermal bridging is the one of main reason for heat losses through the building envelope. Many studies such as [64] and [65] determined that up to 50% of the R-value drops due to thermal bridging, thus the “series and parallel heat flow paths” are applied in this study in order to take into consideration the thermal bridging so-called “R-value of whole” wall, therefore the total R-value is as following [66]:

$$R_{total} = R_i + R_{whole} + R_o \tag{3}$$

Moisture control in the building envelope could lead to extended durability as moisture can enter a building envelope through different mechanisms including built-in moisture, water leaks, rain, capillary, water vapor diffusion, and condensation. Our focus in this study is only on water vapour diffusion through exterior walls. However, depending on types of moisture, the control would be varied, for instance, by installing appropriate materials that act as a so-called water barrier membrane, the migration of liquid could be stopped. It should be noted, however, that water vapor diffusion has a different mechanism; therefore, in this paper we consider its transformation and overall moisture content through the exterior wall over a four year simulation via WUFi software. Fick’s Law of diffusion is applied as below where *w* is the total water vapor transferred over time of ϴ through each layer [67].

$$w = \mu . A . \Theta . \frac{(P_1 - P_2)}{l} \tag{4}$$

Based on temperature gradient through wall and water vapor pressure, the likelihood of condensation will be calculable. In addition, all case studies are modeled by WUFi software in order to find the moisture accumulation due to condensation over a period of time.

In terms of heat and moisture combination equations (5) and (6) are presented as follows [68]:

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla(k\nabla T) + h_v\nabla\left(\delta_p\nabla(\varphi P_{sat})\right) \tag{5}$$

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla\left(D_\varphi\nabla\varphi + \delta_p\nabla(\varphi P_{sat})\right) \tag{6}$$

Where H, T, w and ϕ represent enthalpy, temperature, moisture content, and relative humidity, respectively. P_{sat}, k, h_v, S_p and D_ϕ are the saturation pressure, thermal conductivity, evaporation enthalpy of water, water vapor permeability, and liquid conduction coefficient, respectively.

Furthermore, the eQuest software [69] is used for energy consumption on a yearly basis in buildings. In energy modeling only, the space heating or cooling (in this case only space heating) is associated with exterior walls, although the walls to windows ratio plays a crucial role in space lighting during the day but we do not consider it here as we only assume that the windows to wall ratio is 35% according to ASHRAE recommendation.

3.2 Life cycle cost (LCC) analysis and boundaries

Life cycle cost is a great approach to evaluate a product's cost over its entire life from initial cost, maintenance and operation, and disposal to the end-of-life. Because of some contributing complexities including inflation, market fluctuations, and other relevant factors, the task of analyzing the cost of building materials and systems in a house is such a great challenge [70]. Accordingly, the approach for analyzing cost in this study is divided into several main areas including, (1) demolition and construction works. (2) Energy consumption on space heating over use phase. Therefore, the initial cost to construct the building (as in our case study) is based on material quantities by quantity surveying and then using the RSMeans database as a reasonable method to estimate the initial cost of construction in terms of prices of building materials and labor. However, at the building's end-of-life, the demolition phase, or disposal, will be part of the deconstruction and the costs associated with it can be found in the RSMeans database, as well. In order to make it clear, Figure 3 illustrates the boundary of this study on LCC, where the construction phase's soft cost and land are excluded. In contrast, labor, energy, equipment, and material costs are taken into account to build a single family house in Montreal as a case study. Over use phase when the building is on operation only space heating cost is considered because other aspects do not receive direct influence from exterior walls. Although maintenance of exterior walls varies based on this kind of material, in this case our focus is more on hygrothermal performance that does not related to it. Finally, at the building's end-of-life, we consider all works in order to demolish the building and transport final materials to a landfill or recycling facility.

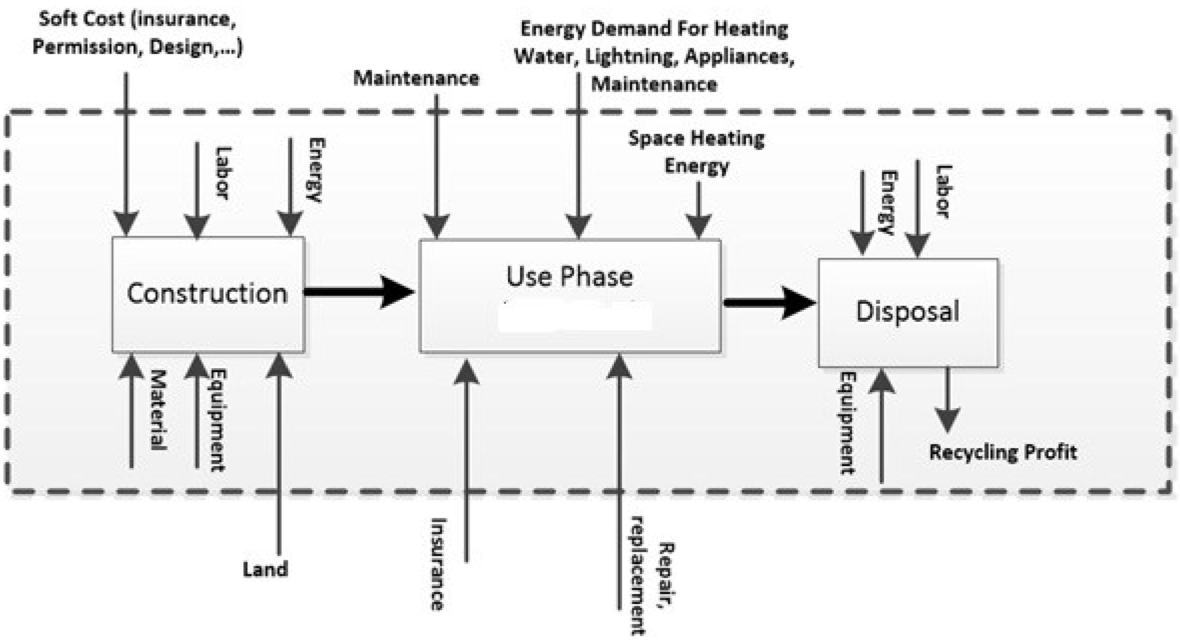


Figure 3 the dotted line represents our boundary of life cycle analysis in this study

In this study, in equation (7), we consider the inflation rate (I1), the interest rate (I2), and the real interest rate (I) equal to 2.1% [71], 4.5% [72], and 2.4%, respectively. According to the Bank of Canada and inflation is the mean of inflation over 25 years which is presented in Figure 4, and also the interest rate is considered nearly 4.5% Figure 5.

$$\mathrm{I} \;=\frac{(1+\mathrm{I}_2)}{(1+\mathrm{I}_1)}-1 \qquad (7) \qquad \mathrm{I} \;=\frac{(1+0.027)}{(1+0.021)}-1=2.4\%$$

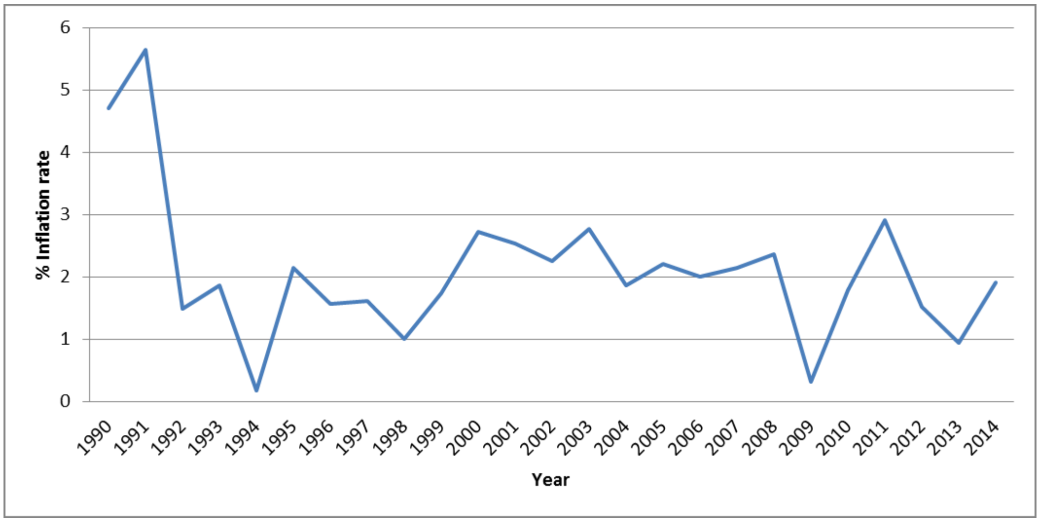


Figure 4 inflation rate

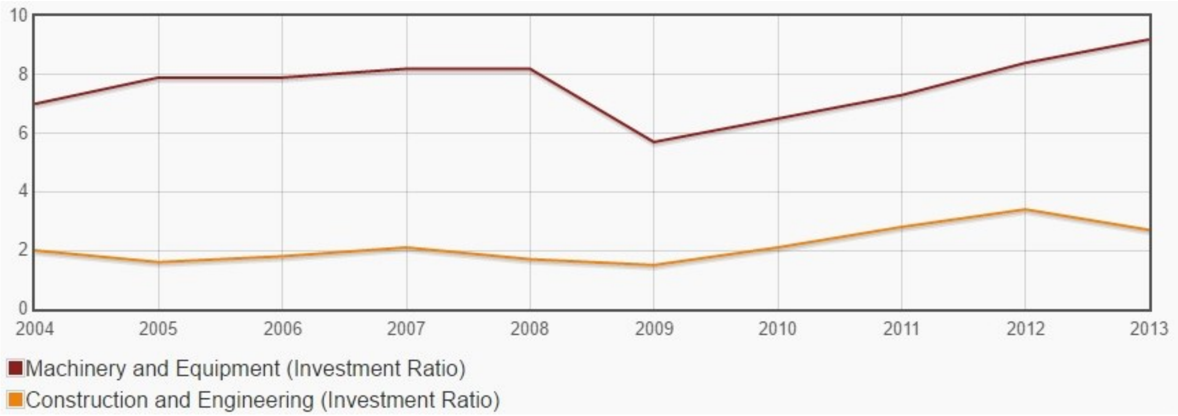


Figure 5 inflation rate and investment ratio (%) by type of asset (2003-2013) in Canada

The energy price is considered nearly \$0.095KWh according to Hydro-Quebec [73] (a public utility in Montreal) website for a residential house in 2016. As mentioned earlier, in this study only energy consumption on space heating is taken into consideration for which this energy demand is calculated by eQuest as an energy modeling tool. Life span is assumed to be 65 years for case studies and the price remains constant over these years in order to make a similar comparison between alternatives. In order to make an appropriate comparison, the overall cost of building is considered as a net present value in each phase of building such as pre-use (construction), use, and end-of-life. In this context, the cash flow method is applied in order to take into account the present net value as following:

$$\text{LCC} = \text{Investment cost} + \text{65 Years of Space Heating Cost} + \text{Disposal Cost} \quad (8)$$

Where the space heating and disposal cost are actually future values (F) which are converted to the present value (P) based on following equation.

$$P = F*(P/F,I,N) \quad (9)$$

Where (P/F, I, N) is called discounting factor over 65 years (N). In fact, there will be many changes in energy price as well as the replacement or repair costs of the exterior wall, whereas they are assumed to be constant in all calculations.

Referring to several studies [74] and [75], the demolition cost for a single family house is taken into account as 5% of the initial construction cost [76].

3.3 Life cycle assessment (LCA) and boundaries

The life cycle assessment is part of the ISO 14000 environmental management standards, which it is considered a powerful approach for evaluating the environmental impact of a product from raw material extraction, transportation, production, distribution, use, repair and maintenance, as well as recycling or disposal. These cycles are called cradle to grave processes. The LCA comprises of four main stages as it is shown in Figure 6: 1) Goal and scope, 2) Inventory analysis, 3) Impact assessment, 4) Interpretation [77]. The goal and scope stage in this study is assessing the environmental impact of a building with specific exterior walls from construction, energy demand on space heating over use phase, and finally, disposal after 65 years of operation. For clarification, Figure **7** shows the boundary of this study on LCA.

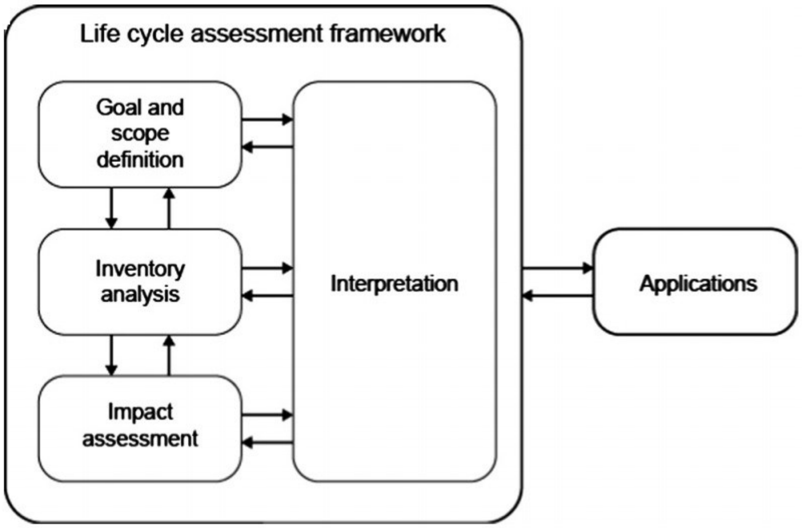


Figure 6 different Phase for LCA [41] and [78]

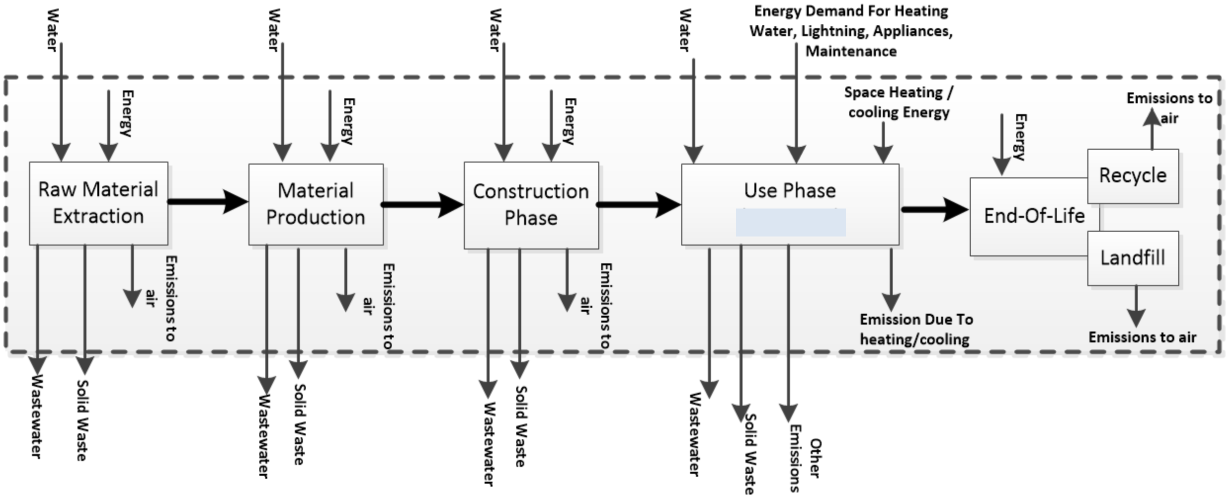


Figure 7 life cycle assessment boundary in this study.

This boundary was defined to determine all energy use and global warming potential (GWP) over the entire life of our case study despite that in use phase only space heating energy is included and other energy demands are excluded. The reason for this boundary is that we take into consideration only aspects or consequences of exterior wall influences.

In the second stage, various elements based on quantities surveyed of building materials, construction phase, space heating energy consumption during use phase, and, finally, the disposal of the building, will be assessed to determine the amount of emissions cast in air, as well as energy demands at each phase of building. Two environmental indicators are applied for this impact assessment including greenhouse gas emissions (Global Warming Potential), and total energy consumption [79]. GWP is calculated using the greenhouse gas emission equivalent of Carbon Dioxide:

$$\text{Global warming Potential (kg)} = \text{Carbon Dioxide (kg)} + \text{Methane(kg)} * 23 + \text{Nitrous Oxides(kg)} * 296 \quad (10)$$

Life cycle energy in terms of primary energy is considered as following equation [80]:

$$\text{Primary energy (life cycle energy)} = \text{Embodied energy} + \text{Space heating energy} \quad (11)$$

Finally, in the last stage, the results are interpreted based on their impact and consequences. This interpretation would be a holistic view of inventory results, environmental indicators, and consequences of effect, along with a recommendation where of ranking exterior wall alternatives based on their contribution on environmental impact in terms of primary energy and GWP.

In order to assess the environmental footprint of our case studies, we use Simapro software with all its features. Moreover, the energy demands on space heating is based on the results of the eQuest software which plugs into Simapro for 65 years to see the GWP, as well as total energy demands, of all alternative walls [81].

3.4 Decision analysis with ANP method

The analytical network process (ANP) was introduced by Saaty in 1990 as a multi-criteria theory decision-making process of absolute numbers [61], which are shown in Table 2. This measurement is derived from individual judgments or from actual measurements through a pairwise comparison with respect to an underlying control criterion. It is a new generation of AHP with a multi-directional network.

Table 2 scale of absolute numbers in pairwise comparison

Intensity of importance	Definition
1	Equal importance/preference
2	Weak
3	Moderate importance/preference
4	Moderate plus
5	Strong importance/preference
6	Strong plus
7	Very strong or demonstrated importance/preference
8	Very, very strong
9	Extreme importance/preference

The main differences between ANP and AHP [82], as illustrated in Figure 8 , is that ANP does not have a hierarchical structure allowing the model complex decision-making processes where there are interactions between criteria. Technically, the ANP consists of a structure with clusters (main criteria), the sub-criteria, alternatives, and inter-relationships and dependencies between these decision components [60].

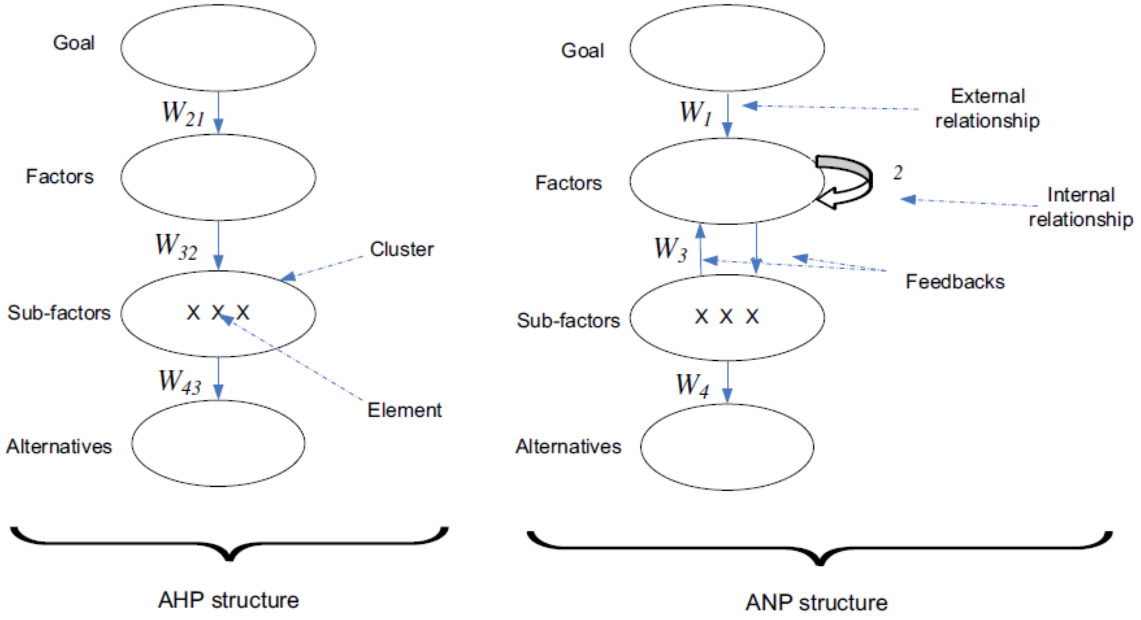


Figure 8 illustrates AHP and ANP structures [82]

As mentioned, there are pairwise comparisons among elements, all of which are collected in a matrix. This matrix is called the super-matrix as it represents the influence priority of an element on the left of the matrix on an element at the top of the matrix where all numbers are the result of pairwise comparisons as indicated in Figure 9. Where component h, denoted by C_h, h =1,2,...,N, has nh elements, that we denote by eh1, eh2,…ehn. A derived vector from a paired comparison will represent the priority of elements in a component on another element in the system which is shown with Wij in super-matrix. If there is no influence between two elements, it is assigned a zero in the super-matrix [83].

Checking the consistency ratio: after constructing the super-matrix, the consistency of this matrix should be checked to determine that all paired comparisons of components are consistent. To clarify what consistency means, here is an example: let's assume number A is greater than B. And also B is greater than C; therefore, A must be greater than C. Consequently, pairwise comparisons are performed between many elements, at the end of which we should somehow control their accuracy in terms of consistency.

According to the literature, CR is called consistency ratio as following [84]:

$$CR = \frac{CI}{RI} \tag{12}$$

Where CI is consistency index based on equation (13).

$$CI = \frac{\lambda \max - n}{n-1} \tag{13}$$

Where n is order of matrix, and λmax is eigenvalue of corresponding columns in super-matrix. RI is random index which can be obtained from Table 3 as associated with order of matrix.

Table 3 RSI values

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

At the end, if CR is less than 0.1 the super-matrix is consistent. Otherwise for CR> 0.1, we should check or revise all pairwise comparisons between elements.

$$
W = \begin{array}{cc}
 & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \\ e_{11}\ e_{12}\ \cdots\ e_{1m_1} & e_{21}\ e_{22}\ \cdots\ e_{2m_2} & \cdots & e_{n1}\ e_{n2}\ \cdots\ e_{nm_1} \end{array} \\
\begin{array}{cc}
C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{array} \\
C_2 & \begin{array}{c} e_{21} \\ e_{22} \\ \vdots \\ e_{2m_2} \end{array} \\
\vdots & \vdots \\
C_n & \begin{array}{c} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_1} \end{array}
\end{array}
&
\begin{bmatrix}
W_{11} & W_{12} & \cdots & W_{1n} \\
W_{21} & W_{22} & \cdots & W_{2n} \\
\vdots & \vdots & \vdots & \vdots \\
W_{n1} & W_{n2} & \cdots & W_{nn}
\end{bmatrix}
\end{array}
$$

Figure 9 General form of super-matrix

Referring to many articles which have already applied ANP methodology, the ANP method consists of four main stages: (1) decision network with all interactions (2) pairwise comparison and calculating e-Vectors (3) super-matrix formation and transformation (4) prioritizing alternatives by interpreting the final results. Moreover, in order to define the accuracy of final ranking in ANP approach a sensitivity analysis is usually carried out.

So far in this section, the network construction and pairwise comparisons were explained. In the third stage, we should do many calculations in terms of super-matrix formation and transformation as these super-matrix calculations will lead to a synthetic matrix as follows. Overall, there are three matrices here including super-matrix, weighted matrix, and limited matrix (or synthesised matrix). The weighted matrix is obtained by multiplying the cluster priority matrix, which is kind of paired comparison or priority of main criteria respect to control criteria by the super-matrix and then normalizing it. This weighted matrix is shown in Figure 10 [85], where t^{s}_{nn} is the elements in the cluster matrix. The reason for multiplying the cluster matrix by the super matrix is to determine their relative overall weight among all the elements in the other clusters.

$$W_w = \begin{bmatrix} t^s_{11} \times W_{11} & t^s_{21} \times W_{12} & \cdots & \cdots & t^s_{n1} \times W_{1n} \\ t^s_{12} \times W_{21} & t^s_{22} \times W_{22} & \vdots & & \vdots \\ \vdots & \cdots & t^s_{ji} \times W_{ij} & \cdots & t^s_{ni} \times W_{in} \\ \vdots & & \vdots & & \vdots \\ t^s_{1n} \times W_{n1} & t^s_{2n} \times W_{n2} & \cdots & \cdots & t^s_{nn} \times W_{nn} \end{bmatrix}$$

Figure 10 weighted matrix where W_{ij} already normalized and then multiplied by cluster matrix elements

After the normalization of the weighted matrix, it is raised to a significantly large number until the weights converge and remain at stable values. The reason for raising to power is to capture the transmission of influence along all possible-paths of the super-matrix. For clarification, one element has an effect on another element that can interfere by considering a third element in which occurs by a fourth element, wherein the following can influence the second element. In this sense, these kinds of influences are consequences of a cubic power of matrix, and so on. Therefore, there is an infinite influence matrix which is identified by W^k (where k=1,2,…). The Cesaro sum is obtained by taking the limit of the average of a sequence of N of these matrices' powers as follows:

$$\lim_{k\to\infty} \frac{1}{N} \sum_{k=1}^{N} W^k, \qquad (14)$$

Where, its result converges to a limit value.

Consequently, by raising this normalized matrix to the power of an infinite number (a significant number) in which all numbers in the matrix are less than one, this raising to power will converge to a constant value in each row. By multiplying the initial matrix W by W^{∞}, the outcome would be the same as W^{∞}, meaning that finding this constant relative value of raising the matrix to power of a very large number would converge to stable values. The values of this limit matrix represent desired priorities of the elements with respect to the goal.

4 Case study

4.1 Background

In this thesis we are assessing three alternative walls: ICFs, PICP, and wood-frame, as shown in Figure 1. All elements of these walls were designed to meet the building code of Canada in Montreal as well as the ASHRAE standard. Based on specific technologies and methods of implementation, these exterior walls are matched with various insulation materials. , For example, ICFs, PICP, and wood-frame have EPS, rigid PUR, and fiberglass, respectively. The thickness of insulation is chosen to accommodate the RSI-value of $4m^2.K/W$ (R-value=$23ft^2\cdot°F\cdot h/Btu$). This thermal resistance for exterior walls is mandated by the building code of Canada in Montreal based of HDD (4575 Heating degree days below 180C in Montreal).

The polyethylene sheet was placed on the warmer side of the walls to control the water vapour diffusion in cold seasons based on the type of climate related to the geographical location. With the exception of the PICP, the other two walls (ICFs, wood-frame) have rain screens that include an air gap (two centimetres), brick veneer, and a membrane as a water retarder such as Tyvek. PICP does not have a rain screen because during the construction process a water proof substance is added in wet concrete that makes it resistant to water. Additionally, it is impossible or at least very costly to attach a rain screen during manufacturing as a pre-cast in the factory.

In order to evaluate these types of walls, the actual application should be considered. For example, in a single family house, the exterior wall must interact in all aspects (material, load, expansion, contraction, movement, and so on) with the main structure to have a better connection between them. In fact, constructing concrete walls requires a main structure capable of bearing all the dead and live loads while meeting the building code requirements in residential buildings. For example, having a main structure made of wood cannot be constructed with concrete exterior walls that are heavier than wood as it is not easy to design and provide a proper joint.

4.2 Scenarios

Consequently, here we introduce four scenarios as case studies including:

(1) **House type Ⅰ (WW)** is made using wood-frame exterior walls with a main structure made of wood,

(2) **House type Ⅱ (WC)** is made using wood-frame exterior walls with a main structure of concrete,

(3) **Type Ⅲ (ICFs)** is a house made of ICFs exterior wall that are load bearable which act as a main structure, and

(4) The last house named **type Ⅳ (PICP)** includes PICP exterior walls which have the same role as ICFs does i.e. act as a main structure as well.

All these identical houses are a two-story single family house with different exterior walls and structures. The floor plans of these houses are presented in Figure 11 this floor plan was plotted via Auto CAD, in which the total living area is 192 square meters.

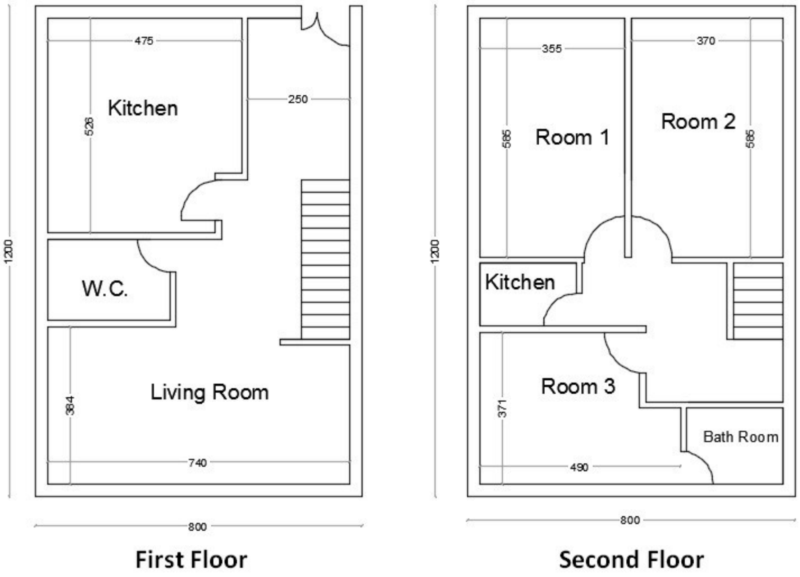


Figure 11 typical floor plan of case studies

Table 4 illustrates the specification of building envelope components. The reason why this building focuses on the building envelope is due to the comparison of the exterior walls which are part of the building envelope and exert influence on energy demands, durability, moisture control and other relevant aspects in buildings. Figure 12 represents a perspective of case study; this 3-D model was obtained from eQUEST.

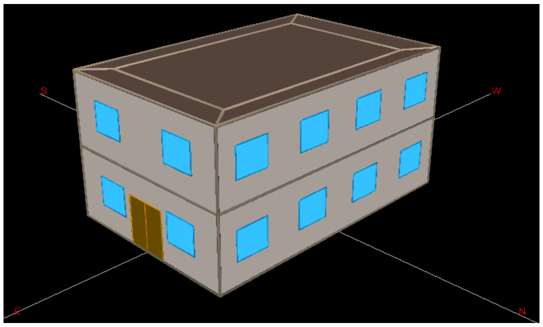


Figure 12 a perspective of case study

Table 4 case studies' specifications

Building Componnents		**ICF**	**PICP**	**Wood-wood**	**Wood-concrete**
Exterior walls		Gypsum board	Gypsum board	Gypsum board	Gypsum board
		Polyethelen sheet	Polyethelen sheet	Polyethelen sheet	Polyethelen sheet
		EPS insualtion	Reinfocemnt Concrete	Fiber glass batts	Fiber glass batts
		Reinforcemnet concrete	PUR insualtion	Wood stud inside fiber galss	Wood stud inside fiber galss
		Plastic Connector inside concrete	Connector inside insualtion	Plywood	Plywood
		EPS insualtion	Exposuree Reinfocemnt Concrete	EPS insualtion	EPS insualtion
		Membrane (Tyvek)		Membrane (Tyvek)	Membrane (Tyvek)
		Air gap		Air gap	Air gap
		Steel connector inside air gap		Steel connector inside air gap	Steel connector inside air gap
		Brick veneer		Brick veneer	Brick veneer
Interior walls		Gypsum board	Identical	Identical	Identical
		Steel or wood stud			
		Gypsum borad			
Roof		Lime mortar+ polyethylen sheet	Lime mortar+ polyethylen sheet	Gypsum board	Lime mortar+ polyethylen sheet
		Reinforcment concrete slab	Reinforcment concrete slab	Wood joist	Reinforcment concrete slab
		Anhydrite screed	Anhydrite screed	Sub flooring playwood	Anhydrite screed
		Bitumen	Bitumen	Blowing insualtion	Bitumen
		XPS insulation	XPS insulation	Air gap	XPS insulation
		Polypropylene Felt	Polypropylene Felt	Wood Rafter	Polypropylene Felt
		Gravel	Gravel	Sub flooring playwood	Gravel
				Bitumen	
				Asphalt shingles	
First floor slab		Wood floor	Wood floor	Wood floor	Wood floor
		wooden square joist	wooden square joist	wooden square joist	wooden square joist
		Anhydrite screed	Anhydrite screed	Wood joist	Anhydrite screed
		Reinforcment concrete slab	Reinforcment concrete slab	Gypsum board	Reinforcment concrete slab
		Lime mortar	Lime mortar		Lime mortar
Groun floor		Wood floor	Identical	Identical	Identical
		wooden square joist			
		Anhydrite screed			
		Reinforcment concrete slab			
		Gravel			
Windows		Double glazing	identical	identical	identical
Door		Wooden door	identical	identical	identical
HVAC system	Heating	Electric baseboard	Identical	Identical	Identical
	Cooling	Not applicable			
	Ventelation	Not applicable			
	Hot water	Electric heater water			
Structure	Beam	Not applicable	Not applicable	Wooden	Concrete 0.3*0.4
	Column	Not applicable	Not applicable	Wooden	Concrete 0.3*0.3
	Foundation	Strip foundation	Strip foundation	Strip foundation	Strip foundation

Other descriptions of these houses: four occupants live in each building; the heating system is electric baseboard without cooling and mechanical ventilation system. In this case study, we do not take into account cooling and ventilation because single family houses in this region usually do not have cooling and ventilation, hence in this study our focus is on space heating which plays a significant role on energy consumption.

In our energy simulation, the geographical location is Montreal and the life span of the house is set to 65 years. Table 5 was estimated for building material quantities based on specification, drawing, and ASHRAE, as well as building code recommendations. The identical windows are double glazed with SHGC values equal to 0.52 and an R-value of 1.76m^2.K/W for optimum energy performance purposes in all case study houses [86]. However, in reality ICFs and PICP usually have a smaller window than a wood-frame would due to structural compliance but in these case studies the size of all windows are the same. In other words, according to the ASHRAE standard, the window to wall ratio should be between 20 to 40% in order to have optimum gains from natural lighting on one hand, and also less heat loss from the windows.

Table 5 building material quantities

Building Materilas	**Thichness m**	**Unit**	**ICFs house**	**PICP house**	**Wood-frame with wood structure**	**Wood-frame with concrete structure**
			Total Quantity	**Total Quantity**	**Total Quantity**	**Total Quantity**
Gypsum board	0.012	m2	351	351	439	351
Polyethelen sheet		m2	266	266	266	266
EPS insualtion	0.07	m2	302	-	151	151
Reinfocemnt Concrete		m3	80	70	23	70
PUR insulation		m2	-	151	-	-
Fiberglass batts		m2	-	-	145	145
Plastic Connector inside		No.	4,000	2000	-	-
Wood stud in wall		m2	-	-	176	176
Plywood		m2	-	-	372	151
Membrane (Tyvek)	0.005	m2	200	-	200	200
Steel connector inside air		No.	2,000		200	200
Brick veneer	0.08	m2	151	-	151	151
Lime mortar		m2	188	188	-	188
Anhydrite screed		m3	12	12	-	12
Wood joist		m2	-	-	82	-
Bitumen		m2	110	110	125	110
XPS insulation	0.15	m2	96	96	-	96
Blowing insulation		m2	-	-	96	-
Polypropylene Felt		m2	110	110	-	110
Asphalt Shingles		m2	-	-	135	-
Gravel		Kg	82,000	82,000	68,000	82,000
Hard wood (floor)		m2	188	188	188	188
Wooden square joist		m2	188	188	188	188
Double glazing		m2	47	47	47	47
Wooden door		No.	9	9	9	9

4.3 Scenarios evaluation

The following section summarizes the results of exterior walls evaluation, which are obtained from two main methods: calculations and computer simulations. All calculations are carried out according to the regulations that are recommended by ASHRAE standard and other relevant references or mandated by building codes (Builder standard practice and regional standard practice). In addition, hourly simulation tools are applied on modelling and simulating the actual behaviour of building envelope on heat, air and moisture migrations as well as environmental impact in terms of total energy and global warming potential by analyzing long term run of all material and system via life cycle assessment (LCA) modelling.

4.3.1 Hygrothermal performance of four scenarios

4.3.1.1 R-value calculation

As it mentioned in the methodology section, there are various R-value for an assembly, indeed the effective one is total thermal resistance, considering thermal bridging as well as air film resistance. Accordingly, thermal resistance calculation is carried out in two different ways: manually and by THERM software, the results are presented in Table 12. According to Building Code of Canada, and ASHRAE guidelines the thermal resistance in exterior walls in Montreal should be as shown in Table 6 in new buildings that R-value of 23 is insulation material for a plain wall.

Table 6 minimum mandated R-value for a house in Montreal.

Reference	HDD Region	Wall R-value	Roof R-value	Fenestration R-value
Building code	4000-4999	23 (Insulation)	31 (Insulation)	2.58
ASHRAE	4500-6499	17.25	27	1.89

These are whole R-value of system (components) which the initial R-value is calculated depending on building material conductivity, summarized in Tables 10 to Table 12 for three alternative exterior walls including ICFs, PICP, and wood-frame. As an example these calculations are presented below for wood frame.

The following environment conditions are assumed:

Outside temperature=-20^{o}c (winter condition), RH= 60%

Inside temperature =+20^{o} c, RH=40%

Heat transfers in one dimension (across plain wall) also in the case of thermal bridging it is considered on two dimensions. Also heat flows through wood frame wall in three paths (1, 2 and 3) as shown below in Figure 13, paths selection depend on the conductivity of elements.

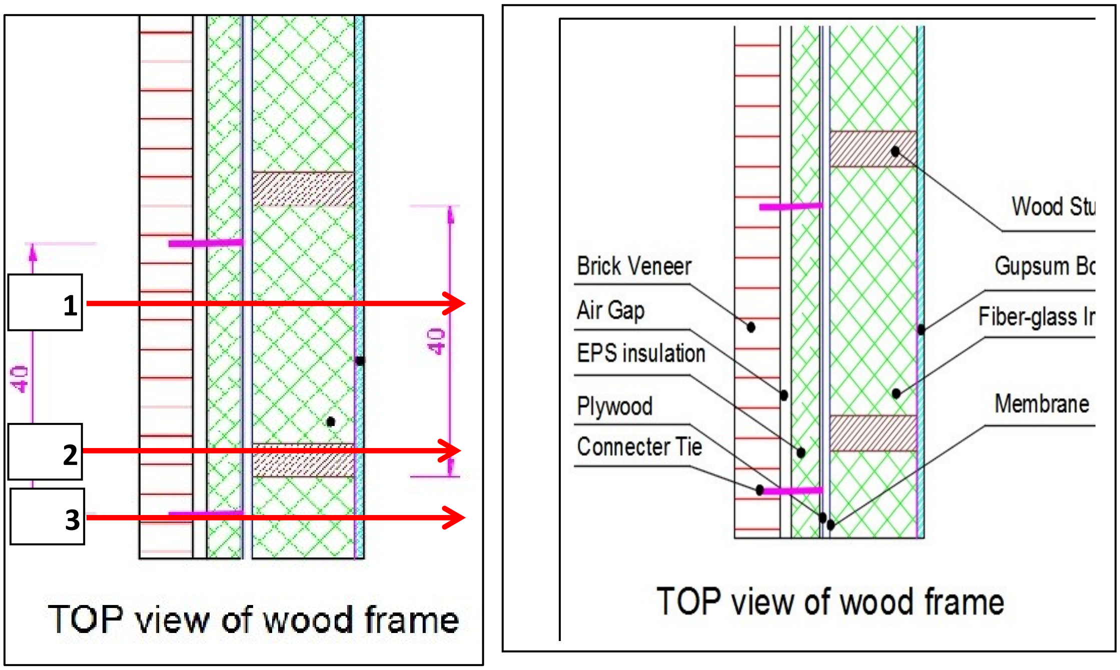


Figure 13 three path of heat flow (Plotted by Auto CAD 2015 student version)

Path 1: R-value of Path1= $\sum_1^n$ Ri = .029+.083+.5+1.215+.014+.14+2.7+.081+.12= 4.883 K.m2/W

See colum5 in Table 7

Table 7 path 1 calculation

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	W/m^2.K	m^2.K/W
Outside Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Air Gap	0.02		2	0.500
Exterior Insulation	0.04	0.033	0.825	1.215
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Insulation	0.15	0.046	0.307	2.700
gypsum board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path1)				4.883

Path 2: Considering the heat-flow through wood stud the calculation is presented in Table 8.

Table 8 heat flow through wood stud

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	W/m^2.K	m^2.K/W
Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Air Gap	0.02		2	0.500
Exterior Insulation	0.05	0.033	0.66	1.515
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Wood stud	0.15	0.16	1.067	0.938
gypsum Board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path2)				3.118

R-value of Path2= 3.118 K.m2/W

Path 3: Heat flows through connecter ties. See Table 9.

Table 9 R-value through path 3

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	W/m^2.K	m^2.K/W
Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Connecter tie	0.07	45.3	647.14	0.002
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Insulation	0.15	0.046	0.307	2.700
Gypsum Board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path3)				3.170

R-value of Path3= 3.17 $K.m^2/W$

Overall R-value: Now based on their area of each path the overall R-value can be computed as below:

A=100*100 = 10000 Cm2

A stud= 2*(5*100) =1000 cm2   There are 2 stud in 1m2 (path2)

Ties= 9*(2*3) = 5.4 cm2   There are 9 connecter ties in each 1m2 (path3)

A plain Wall = 10000-(5.4+1000) = 8994.6 cm2 (this is the plain wall area path 1)

$$U=\sum \frac{Ai}{A.Ri} = \frac{8994.6}{4.883*10000} + \frac{1000}{3.118*10000} + \frac{5.4}{3.17*10000} = 0.1735 + 0.0292 + 0.000170 = 0.216$$

$\frac{1}{U} = R$ and the Overall R = 4.62 Km^2/W this is the RSI-value for wood frame by using 19cm insulation material see the Figure 13 of wood frame wall and its components. This calculation was not taken into account the thermal bridging effects because of wall interfaces with other components, which will be obtained from literature [87], and drops the R-value nearly 15%. Therefore, effective R-value of this wall would be almost 4 Km^2/W.

R-value calculations of ICFs and PICP can be observed in

Table 10 and Table 11, all those calculations are presented in appendix A.

Table 10 thermal resistance of ICFs wall

ICF				
Material	Thickness m	Conductivity W/m.K	Conductance W/m2.K	Thermal resistance m2.K/W
Inside air film	-		8.30	0.1205
Gypsum board	0.0130	0.1600	12.31	0.0813
Polyethelen sheet	-	negligible	-	-
EPS insualtion	0.0635	0.0330	0.52	1.9242
Reinforcemnet concrete	0.1200	2	16.67	0.0600
Plastic Connector inside concrete	0.1600	negligible	-	-
EPS insualtion	0.0635	0.0330	0.52	1.9242
Membrane (Tyvek)	0.0030	0.2100	70	0.0143
Air gap	0.0200		2	0.5000
Steel connector inside air gap	0.0200	45.3	2265	0.0004
Brick veneer	0.0800	1.2100	15	0.0661
Outside air film			34	0.0294
System R-value		-	-	4.5706
Assembely R_value		-	-	4.7205
Whole R_value		-	-	4.5360

Table 11 thermal resistance of PICP wall

PICP				
Material	Thickness m	Conductivity W/m.K	Conductance W/m2.K	Thermal resistance m2.K/W
Inside air film	-		8.30	0.1205
Gypsum board	0.0130	0.1600	12.31	0.0813
Polyethelen sheet	-	negligible	0	0
Reinfocemnt Concrete	0.12	2	16.67	0.06
PUR insualtion	0.1	0.0250	0.25	4
Connector inside insualtion	Negligible		0	0
Exposuree Reinfocemnt Concrete	0.08	2	25	0
Outside air film			34	0.03
System R-value				4.1813
Assembely R_value				4.3311
Whole R_value				4.30

In practice, heat transfers in three dimensions that is not easy to calculate manually, therefore ASHRAE proposes that for getting better results the computer modelling would somehow tackle this issue more practically. In this case, the THERM software was used to model heat transfers through exterior walls as shown in Figure 14 to Figure 17.

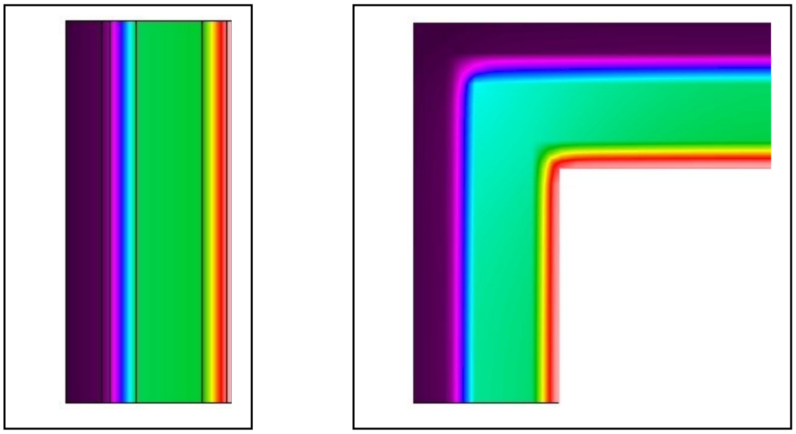


Figure 14 temperature gradient of ICFs wall in corner and clear wall

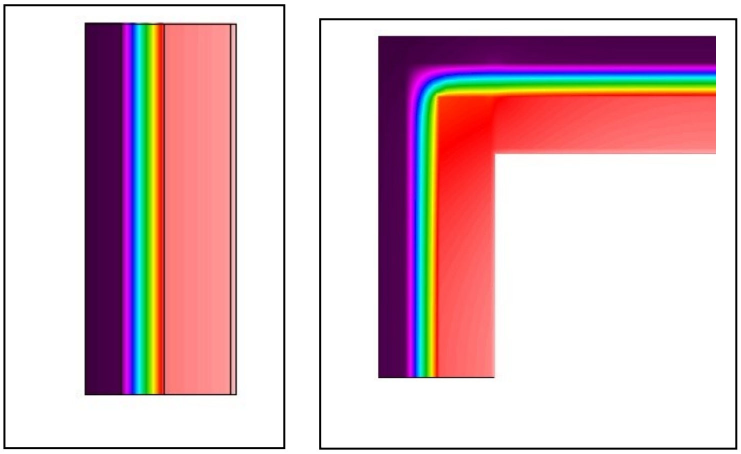


Figure 15 temperature gradient of PICP wall in corner and clear wall

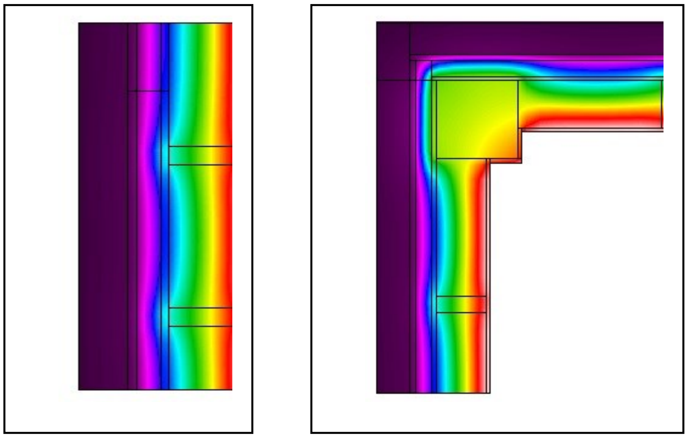


Figure 16 temperature gradient of WC wall in corner and clear wall

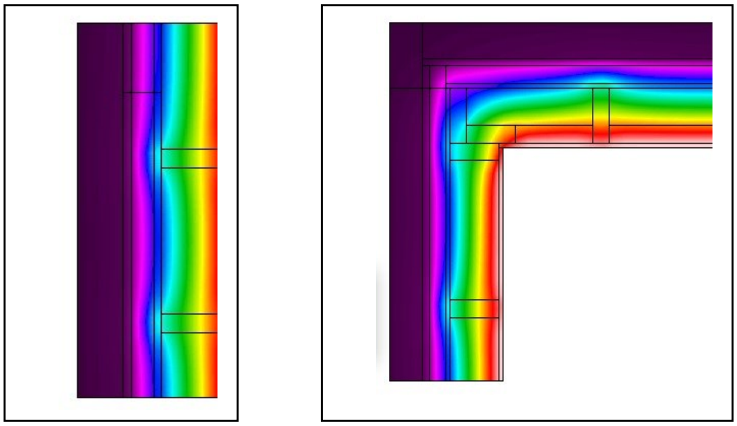


Figure 17 temperature gradient of WW wall in corner and clear wall

Table 12 R-value in clear wall and at the corner of walls

House type	Type of insulation	Insulation thickness (m)	Total R-Value (m^2.K/W)	R-value at corner from THERM (m^2.K/W)	Assembly thickness (m)
ICFs	EPS	0.14	4.54	4.2	0.38
PICP	Rigid PUR	0.10	4.30	4	0.34
WC	Fiberglass	0.20	4	3.6	0.33
WW	Fiberglass	0.20	4	3.8	0.33

All in all, the results of all scenario evaluations in terms of R-value indicated that thermal bridging is one of main reason of heat loss in elements or assembly. For instance, WW and WC houses have 20 centimetres insulation material with nearly R-value of $4m^2$.K/W, while ICFs and PICP scenarios with 14 and 10 centimetres insulation material, respectively, provide slightly higher level of thermal resistance. However, types of insulation materials would vary but nevertheless it proves the fact that type of exterior walls (technology) plays a crucial role than type of insulation material due to continuous layers of insulated concrete technology that do not create a notably thermal bridging. In addition, modelling these walls at corner of the house via THERM software shows that in terms of R-value, ranking would be ICFs, PICP, WW, and WC.

4.3.1.2 Heat and moisture simulation

Basically, there are many measures that should be taken into consideration in order to model a building envelope performance. Those measures are: initial water content of assembly, condensation risk, mould growth, drying rate, heat losses, and ASHRAE-160 criterion. In this study to evaluate all alternative walls we analyse the moisture control which covers overall moisture content, condensation risk, and mould growth over operation of building through simulation via WUFI®PLUS software. Also considering the consequences of heat loss by modelling the energy consumption on space heating using eQUEST 3-65 software, where lower energy demand in identical houses on space heating is, indeed, consequences of preventing of heat losses.

All Parameters that are presented in Table 13 were given to WUFi based model as inputs. Moreover, the software recommendations were used for indoor environment in terms of temperature and relative humidity which varies based on outdoor climate data of Montreal.

Table 13 input parameters for WUFi modeling

Input	**Description**
Material properties of each layer	From ASHRAE tables and WUFi data base
Wind driven rain exposure	70 % rain absorption coefficient
Component orientation and inclination	According to case studies drawings
Initial temperature	Based on WUFi data base recommendations(20^{0C})
Initial moisture content	Based on WUFi data base recommendations (80%)
Calculation period	From 1/1/2010 to 1/1/2014 (4-year)
Outdoor climate	From climate data on WUFi
Indoor environment	Based on Outdoor climate varies

4.3.1.3 Moisture content

The building envelope should be designed and constructed by some means that allows accumulated moisture to dry out, this accumulation occurs either from initial moisture content or others sources (such as condensation, rain, capillary suction, and rain-wind force). The definition of drying potential is the ability of an assembly to dry off moisture content over time. This drying percentage is called drying rate over a specific period of time in this case 4 years. The WUFi based-model simulates the moisture content as illustrated in Figure 18 for all alternatives. The comparison of the results indicates that WW and WC perform better in terms of drying out the moisture.

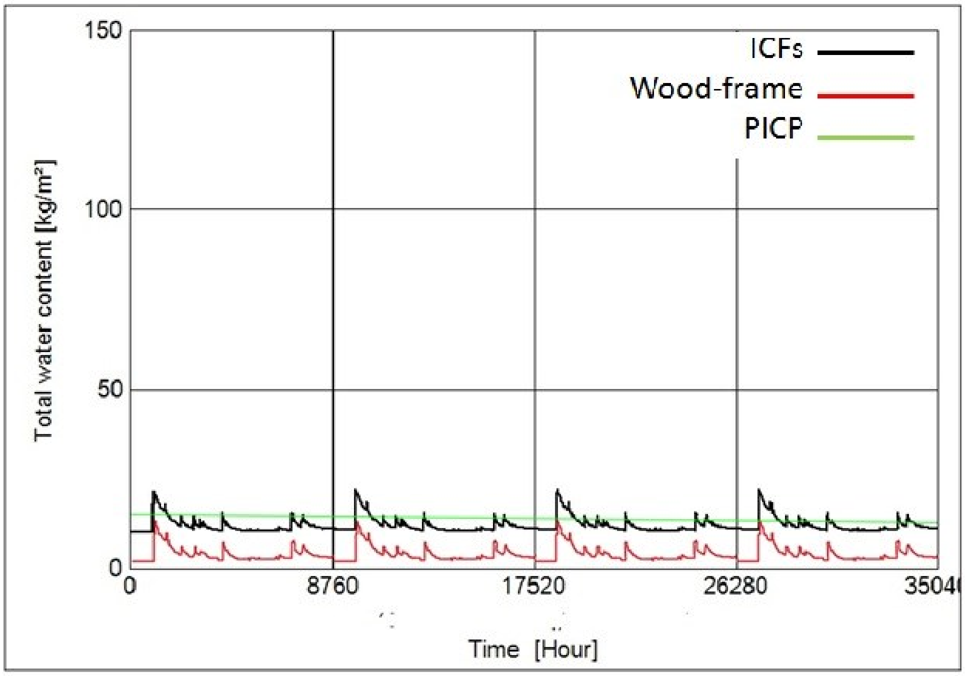


Figure 18 total moisture content

4.3.1.4 Condensation risk

Condensation occurs on surface when the surface temperature is lower than dew point temperature of the ambient air temperature. In order to compare this condensation likelihood, the water vapour pressure in each layer is determined based on vapour diffusion as well as temperature gradient through wall assembly. It means any indoor air temperature corresponds to a maximum capacity of water vapour pressure (vapour saturation), if in this temperature the level of water vapour pressure in air exceeds from this capacity the vapour transforms to liquid, which accumulates on element surfaces of the assembly. Therefore, in order to compare alternative walls in terms of condensation risk we investigate the condensation likelihood through wall assembly. As an example, the Figure 19 shows water vapour diffusion according to equation (4) with three separate calculations for each profile, including condensation, without vapour retarder, with vapour retarder. This figure indicates that condensation likely in wood-frame (with the assumption of inside and outside RH and temperature which are written in the figure) might occur in middle of assembly on plywood surface, in contrast to ICFs and PICP that it might happen on the exterior surface of brick or precast concrete, respectively. It can be concluded that insulated concrete technology controls condensation better than wood-frame. (See appendix B for calculation.). We should emphasize that in this study we did not evaluate condensation occurrence due to air flow through joints and cracks, which is proposed as a future work in conclusion section.

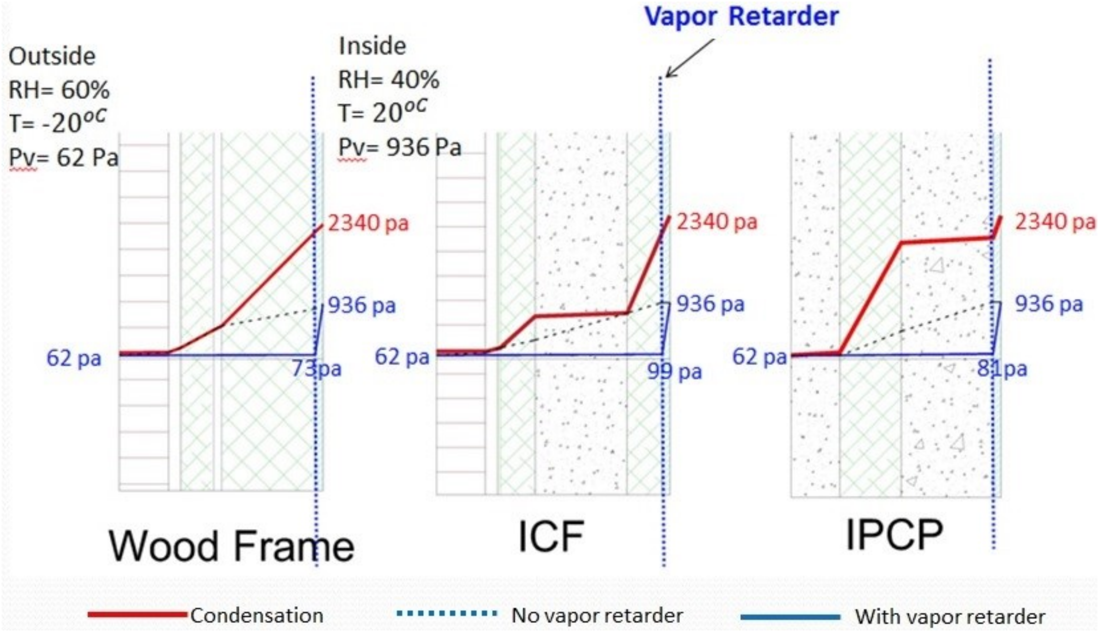


Figure 19 water vapor diffusion through wall assembly (Plotted by Auto CAD 2015 student version)

Obviously, WUFi simulation results will be close to reality, because it takes into account a period of time, that in this case the condensation can be monitored in a specific surface and percentage of time that surface temperature goes below saturation point. Thus, Table 14 defines condensation risk in different selected surfaces including in plywood surface in wood-frame, polystyrene surface in ICFS, and PUR surface in PICP wall. The reason that these surfaces were chosen is based on Figure 19 where condensation occurs at first point from inside.

Table 14 Likelihood of condensation in a specific surface of assemblies

Exterior wall type	**Orientation**	**Specific surface**	**Duration**	**Percentage %**
ICFs	North side	Exterior EPS	4-year	37
PICP	North side	PUR	4-year	38
WW/WC	North side	Plywood	4-year	39

4.3.1.5 Mould growth potential (Controlling ASHRAE 160-2009 criteria)

Many factors cause biological growth in building material, that among these, relative humidity and temperature are principal factors of providing conditions for mould growth. ASHRAE 160-2009 proposes the conditions which are necessary to minimize mould growth, for instance, the following condition should be met: during 30-day RH% must be less than 80% and temperature on surface between 5°C and 40°C as it is indicated in Figure 20, these condition are located in green area.

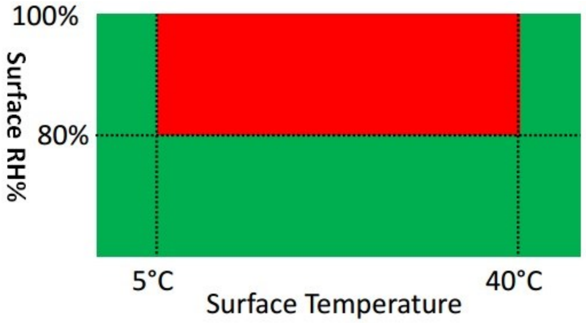


Figure 20 mould growth potential

Through WUFi modelling in the period of 4-year run, it can generate graphs as Isopleths that indicates existence of potential mould growth. In these kinds of graphs there are two term LIM BI and LIM BII, in which the former is for bio-utilizable including wall paper and plaster and the latter term stands for substrates with porous structure such as plaster and mineral building materials. In order to avoid having possibility of mould growth the conditions have to be under these two lines LIM BI and LIM BII.

Figure 21 to Figure 24 present evaluation of mould growth on North orientation for all scenarios as it can be seen in these graphs, there is no possibility of mould growth. However the WC and WW are so below the two lines in comparison with other alternatives. North sides are showed here just as an example and all other sides have almost the same pattern. Although, solar radiation may increase the exterior wall temperature and have influences on inside RH% by evaporation. Evaluating of these phenomena on mould growth is outside the scope of this research and can be seen as a future work.

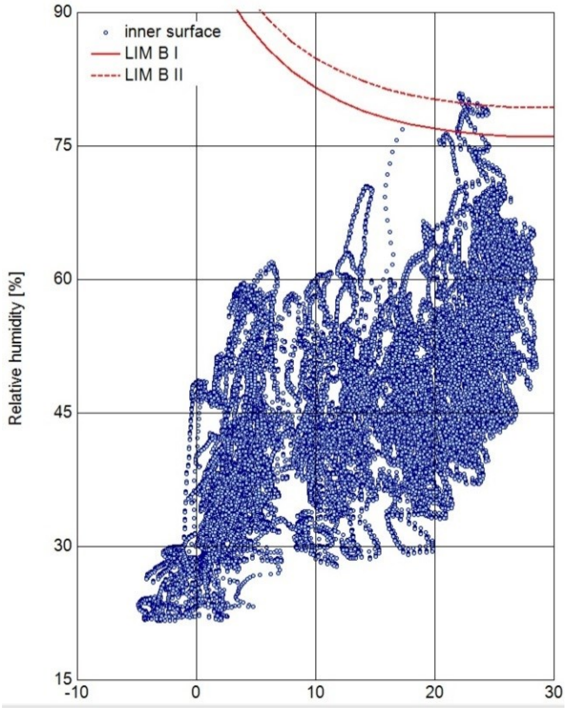


Figure 21 ICF mold growth on North side

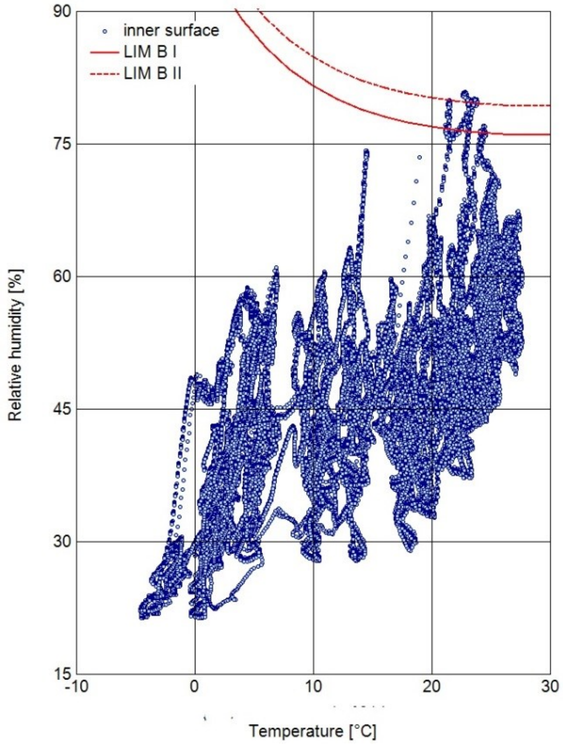


Figure 22 PICP mold growth on North side

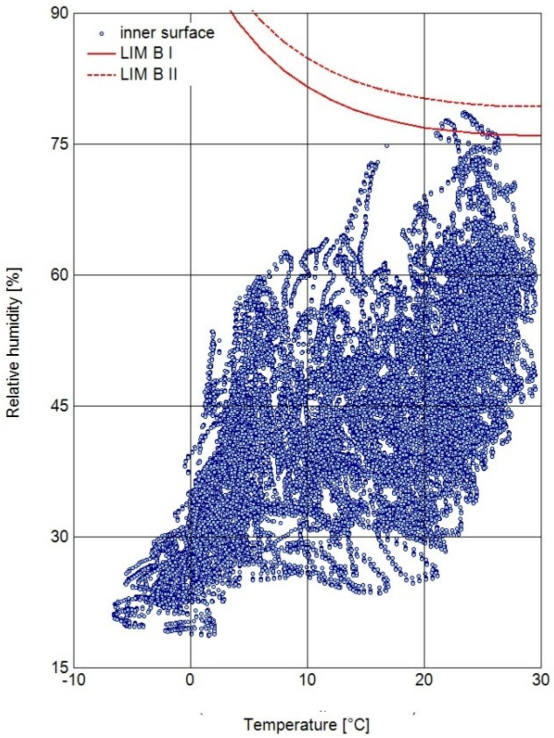


Figure 23 WC mold growth on North side

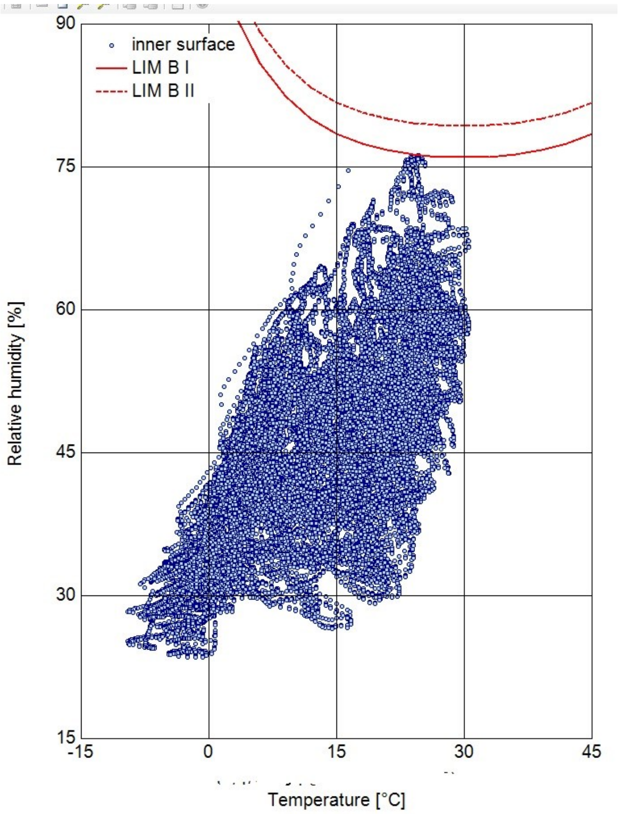


Figure 24 WW mold growth on North side

4.3.1.6 Energy modelling and heat loss

This part turns our focus to thermal performance, while previous parts presented moisture (hygric) performances. The equation (15) usually is applied for heat losses analysis (q) from a wall assembly based of indoor heat transfer coefficient (h_{in}), indoor ambient temperature (T_i), inside surface temperature of wall (T_{si}).

$$q = \sum_{year} h_{in}(T_{in} - T_{si}) \tag{15}$$

However, in this study obtaining annual space heating consumption is conducted through energy modelling tools that is eQUEST software. This energy modelling indicates all alternative contributions on heat losses. The reason is that in our case studies (four scenarios) building envelope was defined in accordance with type of exterior walls, therefore it needs a holistic evaluation in terms of space heating loads. In this sense, eQUEST software has this capability to model energy demand on space heating by creating a virtual environment.

Technically, eQUEST runs building energy analysis by performing hourly simulation of the building based on windows, walls, glass, occupants, plug load, ventilation, lightning, HVAC system, location, shape, and orientation. Indeed, by creating multiple simulations it can provide results of all alternatives side by side graphic. Table 15 and Figure 25 present total annual energy consumption in four houses where the space hating is highlighted in Figure 25. In addition, bar-chart below (Figure 26) compares annually space heating energy usage on four identical single family houses with different exterior walls. The results prove that houses with insulated concrete walls consume lower energy on space heating in contrast with wood-frame, because of their high thermal mass and continuous layers.

Table 15 annual energy demand

Type of energy consumption	**ICFs house** 1000KWh	**PICP house** 1000KWh	**Wood-frame with wood structure** 1000KWh	**Wood-frame with concrete structure** 1000KWh
Annually total	18.20	18.48	19.37	19.58
space heating	9.20	9.51	10.36	10.55
ventalation fan	0.41	0.38	0.42	0.44
hot water	3.22	3.22	3.22	3.22
Area lighting	3.21	3.21	3.21	3.21
equipment	2.16	2.16	2.16	2.16

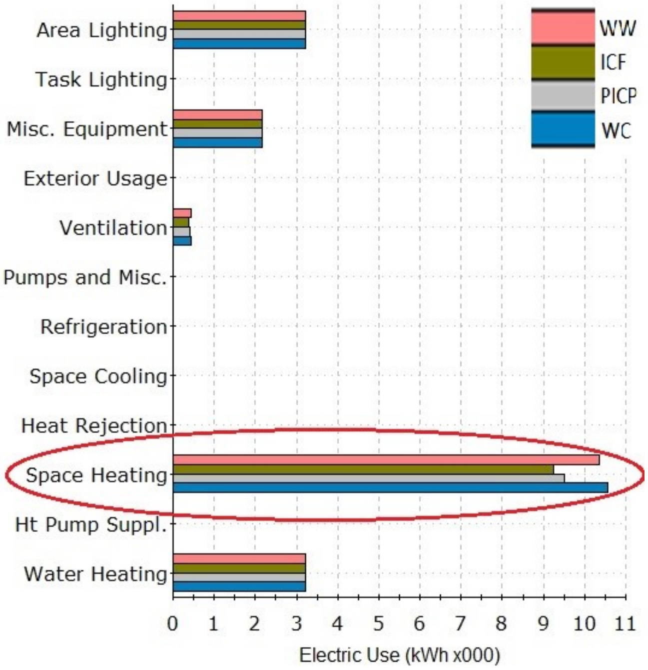


Figure 25 total annually energy usage directly from eQUEST results.

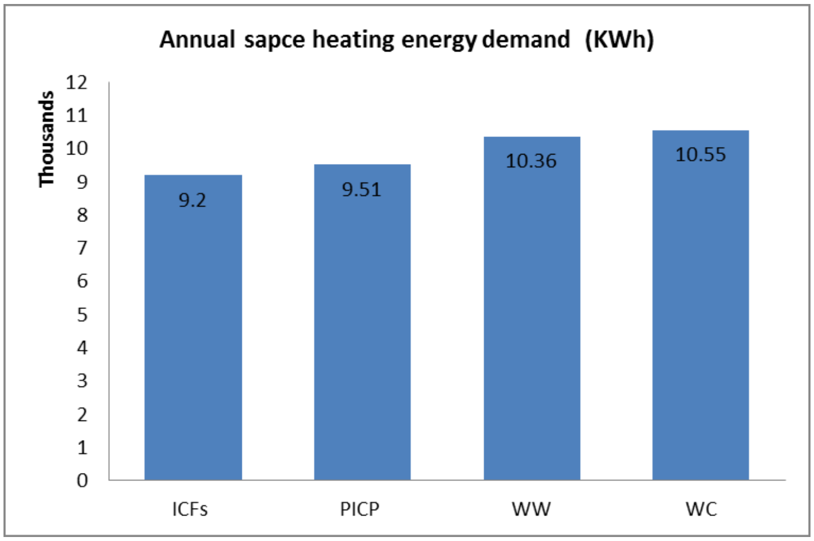


Figure 26 annual space heating energy demand of four scenarios.

Overall, the energy simulation determined that houses with insulated concrete technologies have slightly lower heat losses in building than a wood-frame. This could lead to energy consumption drop on space heating because of higher thermal mass of concrete as well as lower thermal bridging phenomenon. In this modelling approximate reduction of 10% was observed on space heating energy between wood-frame and ICFs.

4.3.1.7 Thermal mass

Thermal mass is defined as capacity of heat storage of a material. It can store and absorb heat to release it later, where this inertia on temperature fluctuations could lead to provide a time lag. The thermal mass depends on density, heat capacity, and conductivity of material. Building materials have various thermal mass that among them concrete is considered as a high-level thermal mass building material. That if combined with proper insulation material as an exterior wall it could lead to energy efficiency on space heating or cooling [25].

As emphasized before, all wall alternatives in this study were assembled in accordance with relevant standards' recommendation. A brief analysis indicates that concrete technology walls have higher thermal mass in one square meter as it is shown in Table 16 thermal mass of building material. In other words, from Table 16it can be concluded that in one square meter of clear ICFs wall the heat capacity would be nearly triple of wood-frame wall (WW).

Table 16 thermal mass of building material

Scenarios	Main thermal mass material				Total heat capacity in a square meret of wall
	Material	Thickness	Dencity	Heat capacity	
		m	Kg/m^3	$K.J/m^3.k$	$K.J/m^3.k$
ICFs	Concrete	0.15	2300	2500	528
	Brick	0.1	1400	1400	
	Gypsum board	0.013	1000	1000	
PICP	Concrete	0.21	2300	2500	538
	Gypsum board	0.013	1000	1000	
WW	Brick	0.1	1400	1400	183
	Gypsum board	0.013	1000	1000	
	Wood	0.035	750	862	
WC	Concrete	0.05	2300	2500	307
	Brick	0.1	1400	1400	
	Gypsum board	0.013	1000	1000	
	Wood	0.035	750	826	

4.3.2 Life cycle cost analysis of four scenarios

LCC analysis is an economic method that addresses whole cost of a product, in this case a single family house in Montreal, throughout a given study period. There are three main cost phases analysis in this study as follows: construction cost, space heating cost, and demolition cost. All these costs are estimated as net present values based on relevant discount factors. The cost estimation in each phase is obtained from RSMeans Constriction Cost 2016 (book) [88], utility grid company or other relevant literature.

4.3.2.1 Construction cost

As boundary was already presented in methodology section, this part presents the initial construction cost of four scenarios. There are two types of information for estimating cost of a construction work. First is quantity of all materials, labours, and equipment according to Table 4 descriptions. And second is unit price for these items. The former is calculated through quantity surveying based on house specification and dimension, the latter one is obtained from RSMeans Building Construction Costs Book [88]. All the costs in Table 17 were obtained from RSMeans as unit cost which includes material, labour, equipment and contractor mark-up. Indeed, we only consider components of the house that somehow related to exterior walls or building envelope type including: roof, exterior walls, windows, interior walls, doors, main structure of house, floor, and slab-on-grade. Table 17 illustrates the initial construction cost for all case studies.

Table 17 initial construction cost for all case studies

Describtion	**Unit**	ICFs			**PICP house**		**Wood-frame with wood structure**		**Wood-frame with concrete structure**	
		Unit Cost	Quantity	Total cost	Quantity	Total cost	Quantity	Total cost	Quantity	Total cost
Gypsum board	S.F.	6.05	1,889	11,429	1,889	11,429	2,363	14,294	1,889	11,429
Polyethelen sheet	Sq	17.75	28	504	28	504	28	504	28	504
EPS insualtion	S.F.	1.67	3,251	5,429		0	1,625	2,714	1,625	2,714
Reinfocemnt Concrete	C.Y.	172.50	105	18,078	92	15,818	30	5,197	92	15,818
Reinfocemnt rebar	Ea	23.50	705	16,568	617	14,497	203	4,763	617	14,497
PUR insulation	S.F.	2.85		0	1,625	4,632	0	0	0	0
Fiberglass batts insulation	S.F.	1.78		0		0	1,561	2,778	1,561	2,778
Plastic Connector inside	L.F.	11.30	260	2,943	130	1,471	0	0	0	0
Wood stud in wall	M.B.F.	2375.00		0		0	1	2,787	1	2,787
Plywood	L.F.	2.27		0		0		4,092		1,661
Membrane (Tyvek)	L.F.	0.33	2,153	710		0	2,153	710	2,153	710
Steel connector inside air gap				700		0		700		700
Brick veneer	M	2400.00	12	27,877		0	12	27,877	12	28,800
Lime mortar	Sf	0.75	2,024	1,518	2,024	1,518	0	0	2,024	1,518
Anhydrite screed				0	0	0	0	0	0	0
Wood joist	L.F.	14.45		0	0	0	883	12,754	0	0
Bitumen	Sq	305.00	12	3,611	12	3,611	13	4,104	12	3,660
XPS insulation	S.F.	2.05	1,033	2,118	1,033	2,118	0	0	1,033	2,118
Blowing insulation	S.F.	3.01		0	0	0	1,033	3,110	0	0
Polypropylene Felt	Sq	278.00	12	3,292	12	3,292	0	0	12	3,336
Asphalt Shingles	Sq	220.00		0	0	0	15	3,197	0	0
Gravel	C.Y.	23.00	49	1,123	49	1,123	40	931	49	1,127
Hard wood (floor)	sf	9.70	2,024	19,629	2,024	19,629	2,024	19,629	2,024	19,633
Wooden square joist	sf	5.60	2,024	11,332	2,024	11,332	2,024	11,332	2,024	11,334
Wooden door	Ea.	486.00	10	4,860	10	4,860	10	4,860	47	22,842
Double glazing	Ea	785.00	18	14,130	18	14,130	18	14,130	9	7,065
Total Price				145,851		109,965		140,466		155,031

Except PICP house which has lowest construction cost, other scenario costs actually are approximately close in terms of initial cost where price of ICFs, WC, WW account for $146’000, $155’000, $140’000, respectively. There is a discrepancy between PICP with other options because there is no brick veneer in PICP wall, that it costs nearly $28,000. Overall, from initial construction cost comparison, PICP and WW are the best options followed by ICFs and WC.

4.3.2.2 Energy cost of space heating

Apace heating often accounts for nearly 60% of total annual energy usage in a Canadian house, that this could be reduced by designing and constructing of a house to control efficient heat loss through building envelope components and gaining more solar radiation through building envelope components. In this regards, exterior walls contribute to heat loss approximately 35% comparing to other building envelope components [89]. In order to find out their contributions on space heating in our case studies we modelled four identical houses with different exterior walls by eQUEST. The outcomes were explained in section 4.3.1.6, thus types of exterior walls would influence space heating load demand. These results are multiplied by the price of energy (here just grid electricity) in Montreal for residential purpose. Table 18 shows the total annual space heating cost.

Table 18 space heating cost in four scenarios

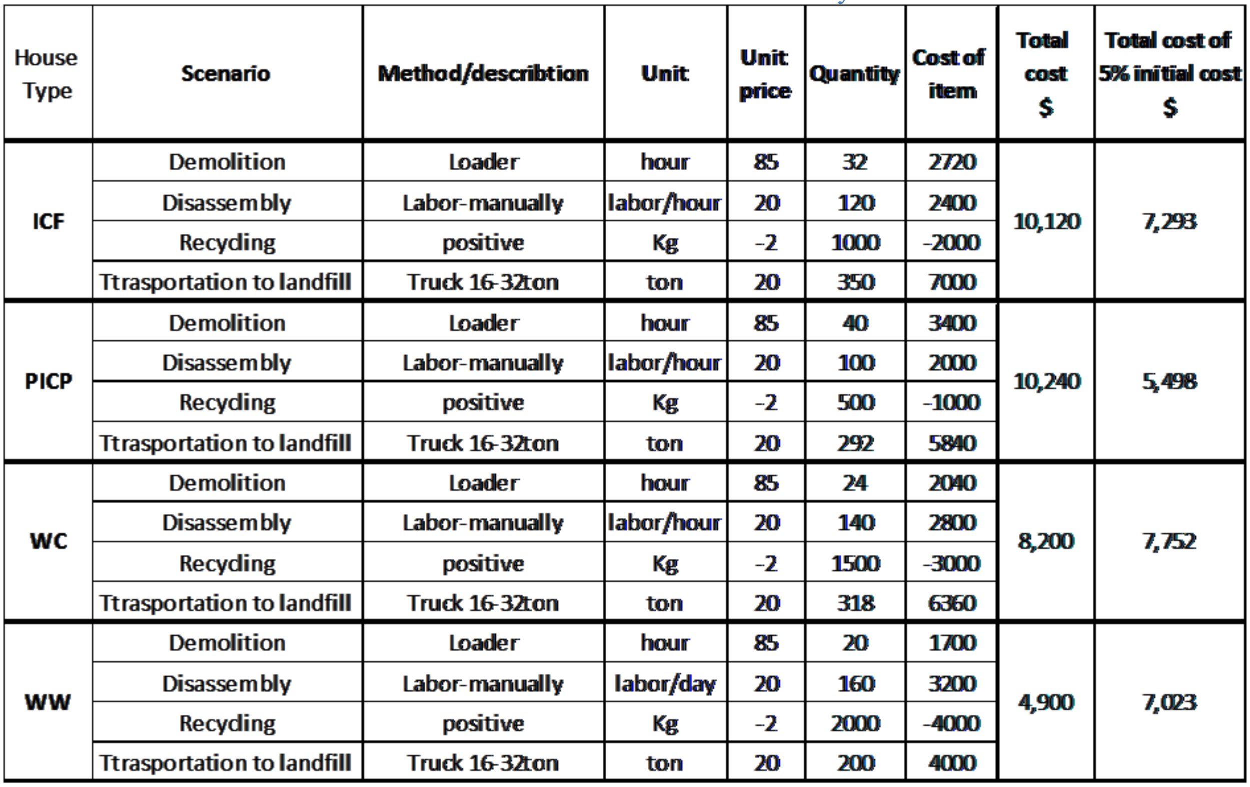
Scenario	Sapce heating KWh	Unit cost KWh	Total annul space heating cost $
ICFs	9200	0.095	874
PICP	9510	0.095	903
WC	10550	0.095	1002
WW	10360	0.095	984

It can be seen that from energy modelling, ICFs has lowest space heating demand in contrast to other choices because, in this type of exterior walls, the thermal mass is placed in middle of the wall with two EPS insulation on either sides as well as continuous layers that control efficiently air movement and thermal bridging. On the other hand, a house with wood-frame walls and concrete structure consumes higher energy on space heating due to thermal bridging and air movement on its interfaces with other components.

4.3.2.3 End-of-the life cost

It is assumed that 65 years of operation would be end-of a house life cycle; therefore the house will be demolished, recycled, and disposed depending on the type of material. Table 19 below estimates the demolition cost of all case studies with two methods (1) demolition and transport all waste to landfill (2) 5% of initial cost according to [47].

Table 19 demolition cost at the end-of-the life by two methods



House Type	Scenario	Method/describtion	Unit	Unit price	Quantity	Cost of item	Total cost $	Total cost of 5% initial cost $
ICF	Demolition	Loader	hour	85	32	2720	10,120	7,293
	Disassembly	Labor-manually	labor/hour	20	120	2400		
	Recycling	positive	Kg	-2	1000	-2000		
	Ttrasportation to landfill	Truck 16-32ton	ton	20	350	7000		
PICP	Demolition	Loader	hour	85	40	3400	10,240	5,498
	Disassembly	Labor-manually	labor/hour	20	100	2000		
	Recycling	positive	Kg	-2	500	-1000		
	Ttrasportation to landfill	Truck 16-32ton	ton	20	292	5840		
WC	Demolition	Loader	hour	85	24	2040	8,200	7,752
	Disassembly	Labor-manually	labor/hour	20	140	2800		
	Recycling	positive	Kg	-2	1500	-3000		
	Ttrasportation to landfill	Truck 16-32ton	ton	20	318	6360		
WW	Demolition	Loader	hour	85	20	1700	4,900	7,023
	Disassembly	Labor-manually	labor/day	20	160	3200		
	Recycling	positive	Kg	-2	2000	-4000		
	Ttrasportation to landfill	Truck 16-32ton	ton	20	200	4000		

Houses that were built with insulated concrete technology are more costly than wood due to their structure and the fact that over time under normal conditions, concrete properties do not change significantly in terms of strength.

4.3.2.4 Life cycle cost analysis

Life cycle cost analysis is carried out by combining the costs such as initial cost, space heating cost, and demolition cost in a cash flow as a present value as it is indicated in Figure 27.

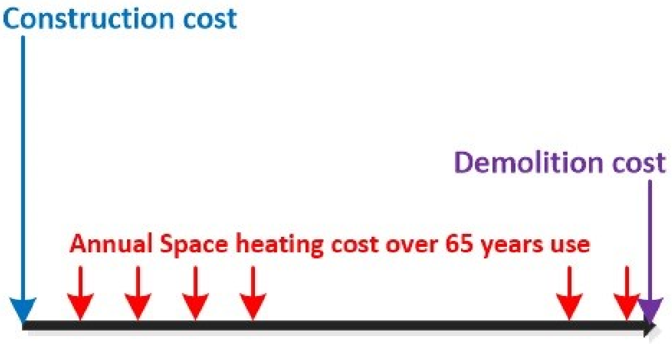


Figure 27 overview of cash flow

This cash flow presents a schematic view of the cost. First is an initial cost, then there is an annual space heating cost, and finally it ends with demolition cost. Referring to methodology section real, interest accounts for 2.4% , while all these potential costs must be considered as present values. These present values are calculated by discounting factor of transmitting future value to present value, which in this case is 31.965. Table 20 presents values of space heating for case studies and all calculations of total present value for scenarios. Overall, it is summarized that space heating cost stands for a significant number over 65 years.

Table 20 presents values of space heating for case studies

House type	Space Heating KWh	Unit Price $	Annually Cost $	Inflation Rate %	Interest Rate %	Real interest Rate %	Discounting factor (65 years)	Present Value $
ICFs	9200	0.095	874	2.1	4.5	2.4	31.965	2,793,741
PICP	9510	0.095	903	2.1	4.5	2.4	31.965	2,887,878
WW	10360	0.095	984	2.1	4.5	2.4	31.965	3,145,995
WC	10550	0.095	1,002	2.1	4.5	2.4	31.965	3,203,692

Table 21 total cost of case studies in terms of present value

House type	Construction cost $	Present value of Space heating cost $	Present value of demolition cost $	Total Cost present value $
ICFs	145,851	2,793,741	7,293	2,946,884
PICP	109,965	2,887,878	5,498	3,003,341
WW	140,466	3,145,995	7,023	3,293,484
WC	155,031	3,203,692	7,752	3,366,475

Taking into consideration of demolition cost as 5% of initial cost, it can be considered as a present value; therefore the summation of all these three present values (initial, space heating and demolition cost) are total cost of all alternatives from construction to disposal which are observed in Table 21. Space heating accounts for highest contribution cost over life span of house that illustrates in Figure 28. It can be concluded that investing more on reduction space heating in general would have notably impact on cost over long term operation in buildings.

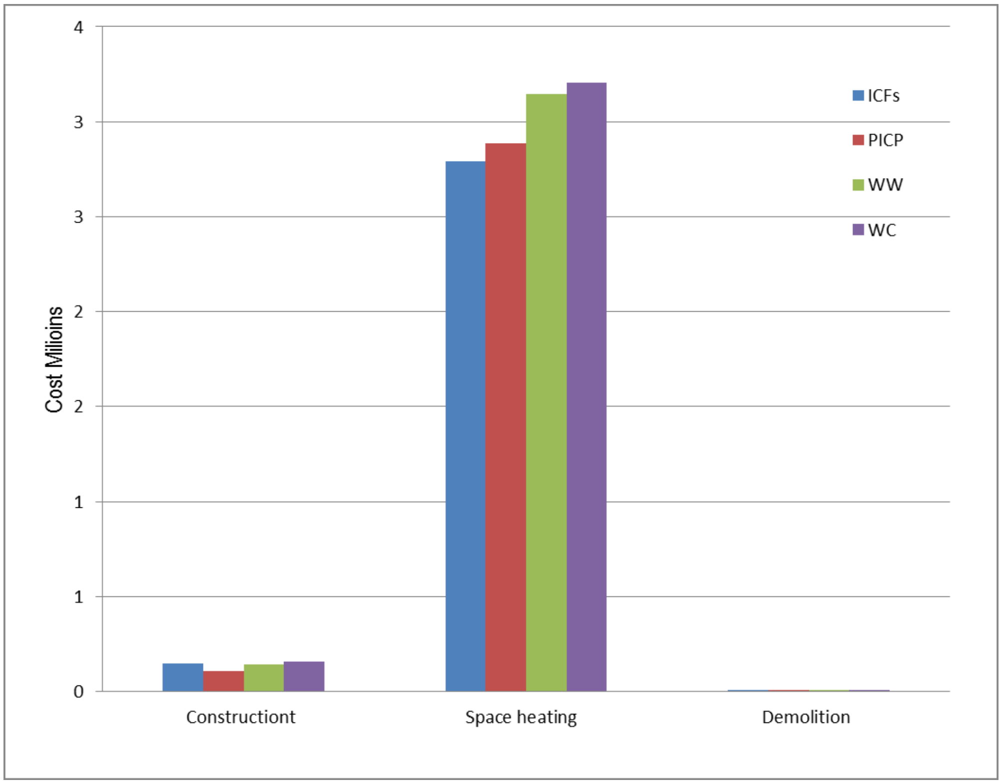


Figure 28 cost comparison of alternatives over entire life span (present value)

4.3.3 Life cycle assessment

As mentioned in the methodology section, in this study we consider two environmental impact indicators for comparing all alternatives on their environmental footprints including total energy demand and GWP. By applying Simapro 8 software, all simulations which are done by this software considers all existing libraries and data, based on historic data of North America construction works.

At first step, goal and scope are defined to address the evaluation of four houses in terms of their impacts on environment on two environment indicators over entire life cycle, where LCA analysis begins with extraction of raw material, energy for transportation to factory, production stage, shipping building material to construction site, construction work, considering only space heating over 65 year, and eventually disposal. Simapro has this feature to calculate building material impacts from cradle-to-gate (from raw material to completion constructing work). For example, there are variety types of concrete in terms of strength, and application in Simapro data base. Here, we consider to use concrete for structure and foundation with 25MPa strength, the ingredient for 1 cubic meter of production and caste in place includes: 279 kg cement, 166 kg water, 1010 kg gravel, 955 kg sand, 21 kg fly ash. Also it needs 65 litres water for a ready concrete that 35 litres is recyclable, 5.74 litres diesel fuel for transportation of ready concrete, formworks and place in cast, which are taken into consideration by Simapro. Other building materials have the same description in Siampro data base.

All building materials are selected from Simapro data base according to each house specification, which is mentioned in Table 17 along with their quantities. Table 22 presents the weight of materials in kg which are plugged into software. After that, shipping distance of these material to Montreal are added as a transportation process which all these distance are shown in last column of Table 22. These distances were obtained through searching online on nearest factory (Google map), provider or producer of building materials.

Table 22 weight of building material and shipping distance from factory to construction site.

Building Materilas	**Thichness m**	**Unit**	**ICFs house**		**PICP house**		**Wood-frame with wood structure**		**Wood-frame with concrete structure**		**Distance Km**
			Mass Kg	**Total Quantity**	**Mass Kg**	**Total Quantity**	**Mass Kg**	**Total Quantity**	**Mass Kg**	**Total Quantity**	
Gypsum board	0.012	m2	3,580	351	3,580	351	4,478	439	3,580	351	600
Polyethelen sheet		m2	77	266	77	266	77	266	77	266	65
EPS insualtion	0.070	m2	740	302		-	370	151	370	151	620
Reinfocemnt Concrete		m3	184,000	80	161,000	70	52,900	23	161,000	70	65
Reinfocemnt rebar		Kg	18,600	18,600	16,275	16,275	5,348	5,348		16,275	160
PUR insulation	0.100	m2	0	-	400	151		-		-	600
Fiberglass batts insulation				-		-		145		145	1,100
Plastic Connector		No.	120	4,000	200	2,000		-		-	620
Wood stud in wall	0.050	m2		-		-	6,600	176	6,600	176	300
Plywood	0.015	m2		-		-	4,185	372	1,699	151	300
Membrane (Tyvek)	0.005	m2	500	200		-	500	200	500	200	1,300
el connector inside air		No.	500	2,000			500	200	500	200	620
Brick veneer	0.080	m2	33,220	151		-	33,220	151	33,220	151	600
Lime mortar		m2	1,241	188	1,241	188		-	1,241	188	65
Anhydrite screed		m3	6,000	12	6,000	12		-	6,000	12	65
Wood joist	0.050	m2		-		-	3,075	82		-	300
Bitumen		m2	990	110	990	110	1,125	125	990	110	200
XPS insulation	0.150	m2	504	96	504	96		-	504	96	620
Blowing insulation				-		-		96		-	65
Polypropylene Felt		m2	495	110	495	110		-	495	110	300
Asphalt Shingles				-		-		135		-	300
Gravel		Kg	82,000	82,000	82,000	82,000	68,000	68,000	82,000	82,000	65
Hard wood (floor)		m2	1,410	188	1,410	188	1,410	188	1,410	188	300
Wooden square joist		m2	4,230	188	4,230	188	4,230	188	4,230	188	300
Double glazing		m2	14,100	47	14,100	47	14,100	47	14,100	47	500
Wooden door		No.	405	9	405	9	405	9	405	9	300

In Simapro by choosing the method (here two indicators) and libraries the results of all three phases will be computed. These are presented in Table 23 and Table 24. At space heating phase just by creating a new run by taking into account corresponding space heating energy of house scenarios based on type of energy. In Montreal 90% of space heating for houses is from electricity grid generated by hydro-power, therefore there is no emission during generation of it, although the infrastructures of this energy supply is not evaluated, in terms of comparing these alternatives it has the same effect on adding to energy.

Disposal of houses after 65years of operation, indeed, is such a construction work on demolition of the house and transportation of the material to the landfill. It can be negligible due to its minor impact on total life and considering the other costs in terms of their environmental footprints.

Table 23 total energy demand from construction, space heating and disposal.

Phase	ICF	PICP	WW	WC
	MJ	MJ	MJ	MJ
Pre-use	1,010,000	743,000	903,000	1,120,000
Space heating	2,152,800	2,225,340	2,424,240	2,468,700
Disposal	30,300	22,290	27,090	33,600

Table 24 global warming potential (GWP) in terms of CO_2 equivalent (Kg)

Phase	ICF	PICP	WW	WC
	CO2 Equi.	CO2 Equi.	CO2 Equi.	CO2 Equi.
Pre-use	**85,000**	**66,400**	**52,300**	**87,700**
Space heating	**0**	**0**	**0**	**0**
Disposal	**4,250**	**3,320**	**2,615**	**4,385**

Figure 29 and Figure 30 are comparing the environmental impacts in terms of GWP and total energy demand (primary energy), overall it can be concluded that space heating over long-term run dominates total energy consumption over entire life cycle, and also thanks to Montreal electricity which is supplied by hydro-power the influence of space heating in GWP is almost nothing. Thus, ICFs would be a best option on consuming less energy follows by PICP, WW, and WC.

Turning to pre-use phase, in GWP, effects of pre-use phase is the major factor of GWP over the entire life cycle. In this case, WW has less concrete and steel; therefore WW has lowest impact on GWP and energy demand than other alternatives. This stage would rank remaining alternatives in the following order; PICP, ICF and WC. Although, disposal phase would be negligible in this comparison analysis.

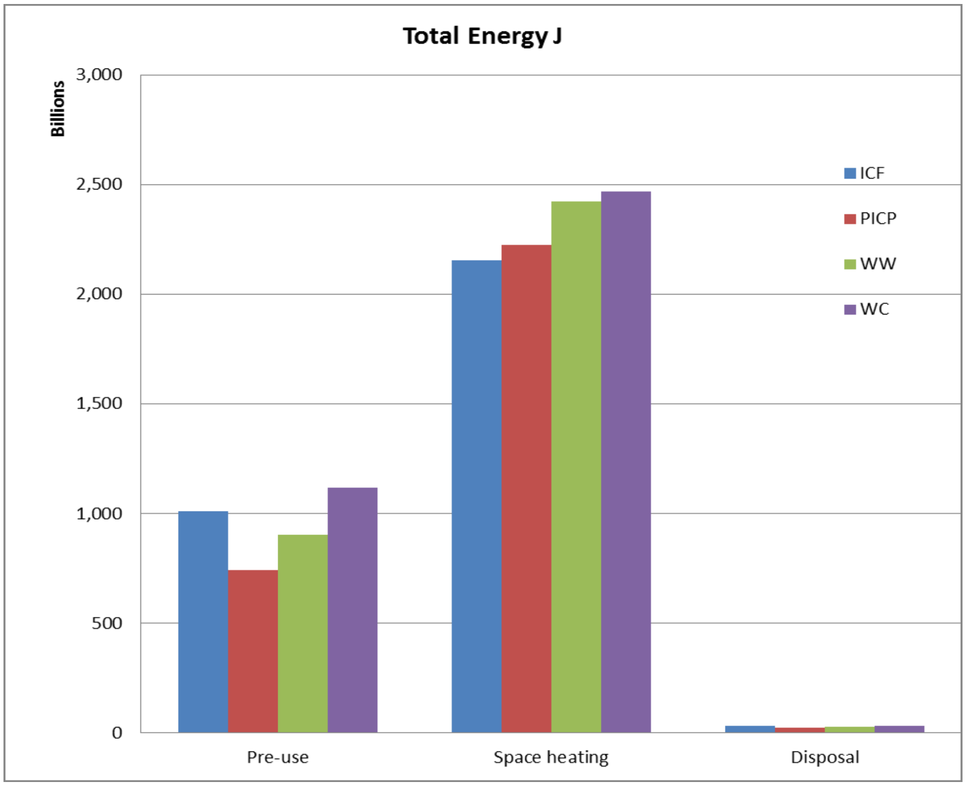


Figure 29 comparison of total energy demand (Joule)

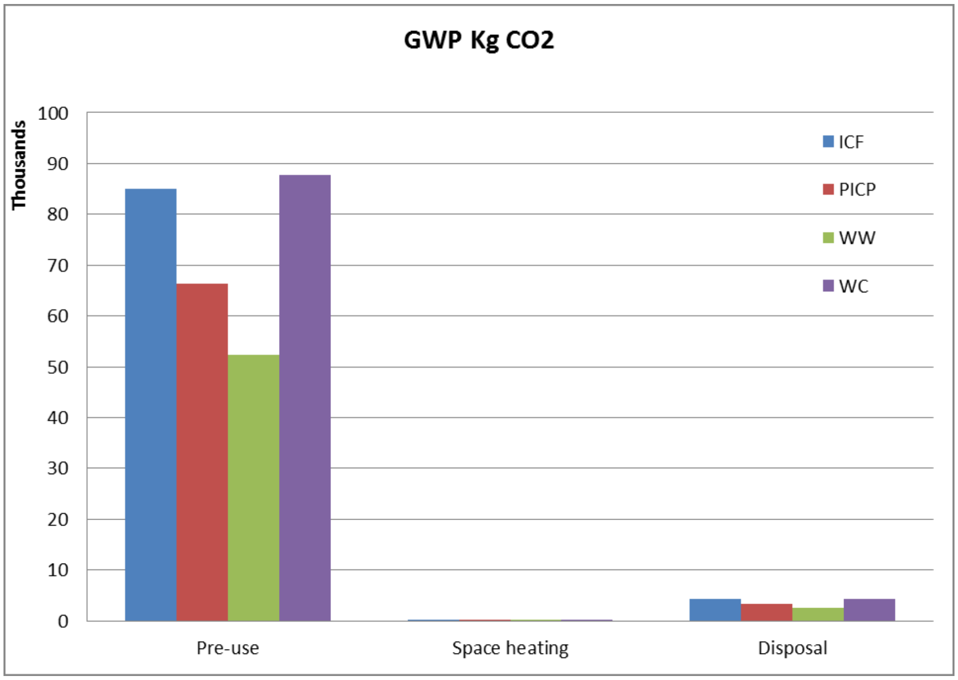


Figure 30 comparison of total GWP per CO_2 equivalent (Kg)

4.3.4 Decision analysis

Referring to all evaluations in this study, by far, it is clear that there is a high level of complexity on determining which exterior wall would be suitable in Montreal. In other words, a proper exterior wall should comply many characteristics including lower price, higher thermal resistance, better control moisture, and less impact on environment. As it found out earlier none of those alternatives have all requirements at once, that a designer should consider them when details a wall assembly specification in a house. Thus, in this section we are trying to find a proper decision making process which provides this flexibility to cover all inter-relationships, dependencies and feedbacks in this study. However, there are 36 MCDM methods (Saaty 2008) [60] to choose a suitable method would be challenging, therefore, first, the ranking of all alternatives will be determined as well as their influences on each other and then the suitable MCDM method will be proposed based on its features and similarities.

Obviously, we need to select one alternative or rank from all other alternatives in order to select the best choice to least under various sub-criterion and observe, overall, which could be a proper choice. As discussed before, in order to choose an exterior wall there are four main objectives, where all these criteria include many sub-criteria that vary with types of exterior walls. Our evaluation determined that there are two types of criteria include measurable criteria (such as cost, total primary energy, Hygrothermal performance, environmental foot prints) and non –measurable that so-called soft criteria (including health aspects and aesthetics). The latter needs experts' judgments. Table 26 shows all these rankings for different alternatives according to actual calculation or measurement which is presented in Table 25. In Table 26 the best option is placed on top of the table, for instance WW has lowest initial price on construction phase; on the other hand, WC stands for highest initial cost. However, the well-being aspects are ranked under experts' judgment, obtained through a questionnaire survey. This questionnaire survey is attached in appendix C.

Table 25 overview of all calculations

Criteria		**Sub-criteria**	**Unit**	**Alternatives**			
				WW	**WC**	**ICFs**	**PICP**
Measurable	Cost	Initial cost	$	140,000	155,000	146,000	110,000
		Space heating cost	$	3,145,995	3,203,692	2,793,741	2,887,878
	Hygrothermal performance	R-value	K.m^2/W	4	4	4.53	4.3
		Thermal mass	KJ/m^3.k	183	307	528	538
		Moisture control	-	-	-	-	-
	Environmental impacts	Total energy	GJ	3354	3622	3193	2990
		GWP	Kg	55,915	92,085	89,250	67,720
Non-measurable	Well-being	Health aspects	-	-	-	-	-
		Aesthetics	-	-	-	-	-

Table 26 ranking of all measurable sub-criteria

Cost		**Environmental impacts**		**Hygrothermal Performance**			**Well-being aspects**	
Initial cost	**Space heating**	**Total energy**	**GWP**	**Moisture control**	**R-value**	**Thermal mass**	**Health aspect**	**Aesthetic**
PICP	ICFs	PICP	WW	WW	ICFs	PICP	WC	WW
WW	PICP	ICFs	ICFs	WC	PICP	ICFs	ICFs	WC
ICFs	WW	WW	PICP	ICFs	WW	WC	WW	ICFs
WC	WC	WC	WC	PICP	WC	WW	PICP	PICP

In addition, to make it clear all criteria and sub-criteria are illustrated in Figure 31 as a network structure. These main criteria, at the first step, are divided into independent categories called clusters. The element of each cluster called sub-criteria, are placed in corresponding cluster. And then their influences on each other in terms of inter-relationship and dependency are determined with a direct line to show their connections or dependencies. The close loop on each main criterion (cluster) shows that there is an inter-relationship between sub-criteria (elements). Dependency between main criteria is illustrated with arrows that could be in one way or two way directions. Alternatives have direct influences on all four main criteria on both directions where changing the type of alternative it can be observed that the main criteria as well as sub-criteria would lead to different rankings. There is an inter-relationship between all sub-criteria in cluster except, well-being that health aspect independents from aesthetics, for clarification, constructing an aesthetic building will not change the health aspects. Also all four types of buildings are independent and scenarios do not influence each other. That is why there is no inter loop in this cluster as shown in Figure 31, this figure was obtained from SuperDecisions software [90]. Hygrothermal performance has a direct impact on environmental impact because higher R-value prevents the heat loss and it causes consuming less space heating energy, on the other hand, the negative impact is that higher level of R-value means utilizing more material that the consequence would be increase on GWP and production energy. Moreover, higher R-value requires more resources on contraction phase that affects initial cost. Hygrothermal performance by controlling moisture will be beneficial on heath and appearance of exterior wall.

Turning to initial cost, considering more resources on construction phase would provide the opportunity to design an exterior wall with less impact on environment and well-being. As mentioned, environmental impacts have direct impact on cost, hygrothermal performance and well-being aspects in terms of total energy and GWP to increase these two environment foot prints we should change the design of assembly where it affects all criteria. Table 27 presents dependencies and relationships among criteria.

Table 27 relationship between criteria

	Alternatives	**Cost**	**Environmetal impacts**	**Hygrothemal performance**	**Well-being**
Alternatives	All four alternative houses are independent, therefore in super matrix in corresponding cells are 0 (zero)	Diret influence on all alternatives	Diret influence on all alternatives	Diret influence on all alternatives	Diret influence on all alternatives
Cost	Diret influence on all alternatives	Initial cost affects on using more quantity of material to reduce space heting to save energy cost on space heting over use phase	Allocating sufficient resurses in order to decrease environmatal impacts by using specific building materials	High level of R-value means increase the thickness of insualtion material where increases initila cost and will drop space heating cost	Aesthetices of a building facad depends on types on building material which has impact on initial cost
Environmetal impacts	Diret influence on all alternatives	Allocating sufficient resurses in order to decrease environmatal impacts by using specific building materials	More total energy demand means increasing the greenhouse gas emision into the air	Higher level of R-value could drop the total enrgy deamd on space heation and increase the embodied energy on pre-use phase	No relationship due to the total energy demand and GWP do not have impact on well-being aspects
Hygrothemal performance	Diret influence on all alternatives	High level of R-value means increase the thickness of insualtion material where increases initila cost and will drop space heating cost	Higher level of R-value could drop the total enrgy deamd on space heation and increase the embodied energy on pre-use phase	Proper level of R-value inffluences the condensation occurrence through wall assembly, thus moisutre control varies with R-value variations	The consequnces of controling the moisture inside assembly would be direct impact on health and apperance of exterior walls
Well-being	Diret influence on all alternatives	Aesthetices of a building facad depends on types on building material which has impact on initial cost	No relationship due to the total energy demand and GWP do not have impact on well-being aspects	The consequnces of controling the moisture inside assembly would be direct impact on health and apperance of exterior walls	There is not any relationship between health aspects and aesthetices

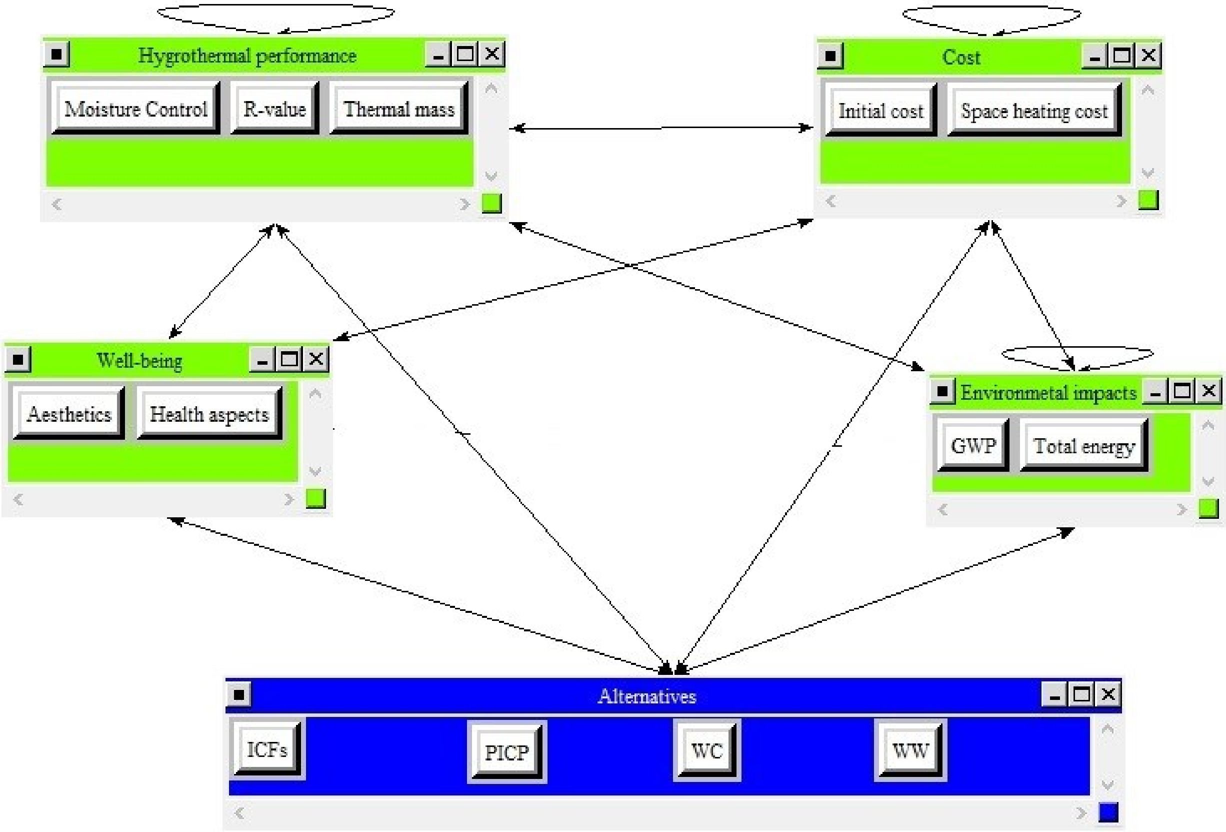


Figure 31 network structure between criteria, sub-criteria, and alternatives

There are two main issues in this analysis to tackle. First is the complexity of all inter-relationships and dependencies between main criteria, sub-criteria, and alternatives. The priority among criteria is the second problem. For instance, comparing the cost with the environmental impacts with respect to type of exterior wall is not an easy task; therefore, the weighted criteria based on their importance needs to be prioritized. Moreover, the goal is to choose the suitable option out of three exterior walls or four scenarios. Accordingly, a multi-criteria decision making approach is used to overcome this complex problem. Thus, in this evaluation the MCDM method must be able to take into consideration the two main aspects: first, all inter-relationships with dependencies (feedback influences), and second prioritizing main criteria. In this case, literature showed that ANP would be a suitable tool. That, these days are being applied by practitioners and researchers in order to make a decision on complex decisions structure. Consequently, at first step to overcome the complexity we should break it down to all those alternatives and criteria with their influence or dependency, as it is indicated in Figure 31 as well as Table 26.

An overview of the ANP method was originally proposed by Saaty (1996) [61]. The main feature of ANP is the flexibility of taking the dependency of the criteria into consideration while calculating the data [91]. The ANP method is applied in order to deal with the restriction of hierarchical structures [92]. The

ANP actually is such a systematic analysis that replaces hierarchies with networks and its approach is based on inter-relationships and dependencies among criteria [93]. As it is obvious that many decision making problems with hierarchy structure are not easy to evaluate because of the complexity of interaction among criteria, therefore ANP would involve in this type of decision-related problem.

4.3.4.1 ANP method

Relevant studies on decision making in building management or construction has been using a variety of MCDM methods [48]. Table 1 summarized several papers whose have studied such complex MCDM methods (or decision-related problem). They are associated with exterior walls, type of structure, and building envelope over the last two decades. These relevant literatures were categorized based on the approach they applied to solve their complexity in accordance with goal and the scope of their researches. Many of those articles used a combination of simultaneous MCDM methods to manage inter-relationships as well as dependencies, in other words, the feedback of influences.

Those MCDM methods render the ANP approach a close fit to our network structure. The ANP mathematical approach is such a powerful method that takes into account pairwise comparison of all sub-criteria, main criteria, and control criteria along with considering the repetition.

The ANP method is chosen as a MCDM method in this study in order to propose an integrated framework on selecting the best overall option. This method has several features and flexibility that could lead to a reasonable result. These features include 1) dependence and feedback 2) allowing for more complex inter-relationship among decision elements and complex network 3) the ability to model a decision problem with conflicting and inter-related criteria 4) capturing indirect influence among elements 5) capability of taking into account two set of measurable criteria and non-measurable criteria [60].

There are two main concerns in our evaluation. First, how to create a structure of hierarchical decision making network, and then how to weigh the decision criteria to address these questions by introducing an integrated framework that the ANP method would provide ultimately. According to basic steps of the ANP method, creating a super-matrix eventually will provide an integrated framework that would contain all possibilities of interaction in terms of pairwise comparisons. These pairwise comparisons consist of two types of evaluations including measurable and non-measurable criteria. Furthermore, this framework is measuring both tangible and intangible factors and determines the dominant elements for each pair with respect to a common property. In this respect, the integrated framework is such a systematic and comprehensive approach for decision making analysis by paving a path from complexity to simplicity.

4.3.4.2 ANP method calculations

The aim of this portion of the study is to select an exterior wall from other alternatives by applying ANP method that includes all mathematical calculations. These ANP calculations consist of four main steps. First is to structure an ANP model that reflects all logic interrelationships and interactions among evaluation criteria. The next step is to qualitatively define all paired connections inside the model based on pairwise comparison for both types of criteria such as measurable and non-measurable where the former criteria are compared based on actual calculation and the latter is done based on experts' judgment. Third, after pairwise comparison and establishing the priority vector in each cluster the super-matrix will be constructed. This super-matrix is ready for formation and transformation. The last step is final prioritization of alternatives. The entire four steps are presented as following for our case studies in terms of numerical and empirical evaluation.

Step 1: Construction of the decision network: the ANP structure was already represented in Figure 31. As it shows there is no a hierarchy structure in this model. This decision-related model presents all interactions between evaluation criteria and alternative in network. There are two key terms including cluster (criteria) and elements (sub-criteria) which are considered to control pairwise comparison. That in each pairwise comparison we should exactly determine which cluster or elements are compared with respect to other cluster or elements.

Step 2: Performing pairwise comparisons: in this step pairwise comparison is carried out based on scale of absolute number that was described in the methodology section. These pairwise judgments derived from two types of data which are collected in the questionnaire survey form experts for non-measurable criteria, or in terms of measurable that it is obtained by calculations along with interpretation. This study already evaluated them in terms of cost, performance and environmental impacts referring to Table 26.

In order to achieve a proper feedback from pairwise comparison four sub-steps are needed including: (a) pairwise comparisons for clusters, (b) pairwise comparisons between clusters/criteria, (c) pairwise comparisons for interdependencies among clusters and criteria, and (e) pairwise comparisons of the alternative evaluations with respect to criteria [94].

Step 2.1: Pairwise comparisons for cluster: This pairwise comparison is carried out in order to determine the decision objectives as the control criteria for a paired comparison matrix. These pairwise comparisons were obtained from geometric mean of experts' judgment through survey. As mentioned earlier in methodology, the pairwise comparison can be rated the component's importance on a scale from 1 to 9 or 1 to 1/9. Table 28 presents the result of cluster comparison through questionnaire each number in this table is a geometric mean of 8 expert opinions through interview. By plugging all these number into a 5*5 matrix the initial matrix of cluster interactions is obtain in Table 29. For clarification, in this case all calculations are described as following steps to obtain a normalized matrix in Table 30.

Table 28 experts' judgment on cluster comparison

Respect to Hygrothemal performance control criterion																			
Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost	0.500
Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environment	0.333
Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hygrothermal	0.200
Alternatives	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Well-being	0.250
cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmetal	0.167
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hygrothermal	0.167
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Well-being	0.143
Environmetal	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hygrothemal	2.000
Environmetal	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Well-being	0.250
Hygrothemal	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Well-being	0.333

Table 29 initial cluster dependencies matrix

	Alternatives	Cost	Environmetal impacts	Hygrothemal performance	Well-being
Alternatives	1.000	0.500	0.333	0.200	0.250
Cost	2.000	1.000	0.167	0.167	0.143
Environmetal impacts	3.000	6.000	1.000	2.000	0.250
Hygrothemal performance	5.000	6.000	0.500	1.000	0.250
Well-being	4.000	7.000	4.000	3.000	1.000

Table 30 normalization of cluster dependencies matrix

	Alternatives	Cost	Environmetal impacts	Hygrothemal performance	Well-being
Alternatives	0.067	0.024	0.056	0.031	0.132
Cost	0.133	0.049	0.028	0.026	0.075
Environmetal impacts	0.200	0.293	0.167	0.314	0.132
Hygrothemal performance	0.333	0.293	0.083	0.157	0.132
Well-being	0.267	0.341	0.667	0.471	0.528

Checking consistency ratio of the comparison matrix we verified equation 12 for the matrix in Table 30, where the result showed the CR equals to 0.005 and is less than 0.1 which is consistence.

Step 2.2: Pairwise comparisons between clusters/sub-criteria: in this step the pairwise comparison is carried out between sub-criteria with respect to their relative influence on a control factor. There are four comparison matrices because of the four existing criteria. These matrices are presented in appendix-B in detail and after normalization we enter this final number into super- matrix. All the numbers in pairwise comparison are obtained from actual calculation, except for well-being aspect which is based on decision makers' opinion that already is derived from expert's judgment.

Step 2.3: Pairwise comparisons for interdependencies among clusters as well as sub-criteria: paired comparison among cluster or sub-criteria follows the same procedure. As described in previous section, the same procedure was applied here in order to take into consideration the interdependencies between sub-criteria. In addition, evaluating the fundamental scale, consistency ratio, geometric mean, and normalizing the priority component W_i to determine the e-Vector. These numbers are plugged into super-matrix after checking all those parameters.

Step 2.4: Pairwise comparisons for evaluating the alternatives with respect to criteria:

Finally, in this type of comparison it should be evaluated the relative influence of each the alternatives on the sub-criteria. Table 30 defines all these pairwise comparison matrix for sub-criteria, for example with respect to initial cost based on previous cost estimation in section 4.3.2.1 in which each alternative that has lower initial cost has higher importance and can be simply ranked according to absolute numbers from ANP method. The e-vector can be obtained by normalizing and checking the consistency ratio. This e-vector is plugged in to super-matrix.

Step 3: Super-matrix formation and transformation: the super-matrix is constructed by inserting all calculated e-vectors in the corresponding columns of a 13*13 matrix. This super-matrix is presented in Table 31. It governs the resolution of the decision network. For instance, according to network in Figure 31 there are not inter-relationships between alternative whose values are zero in the super matrix, and also e-vector of ranking alternatives respect to the initial cost are presented with 0.24, 0.176, 0.305, and 0.0226 correspond to WW, ICF, PICP, and WC, respectively.

Table 31 Super matrix

Cluster Node Labels		Alternatives				Cost		Environmental impacts		Hygrothemal performance			Well-being	
		ICFs	PICP	WC	WW	Initial cost	Space heating cost	GWP	Energy demand	Moisture control	R-value	Thermal mass	Aesthetics	Health aspects
Alternatives	ICFs	0.000	0.000	0.000	0.000	0.176	0.490	0.108	0.244	0.121	0.500	0.421	0.115	0.317
	PICp	0.000	0.000	0.000	0.000	0.357	0.305	0.266	0.545	0.053	0.250	0.421	0.046	0.088
	WC	0.000	0.000	0.000	0.000	0.226	0.079	0.108	0.055	0.413	0.125	0.106	0.342	0.347
	WW	0.000	0.000	0.000	0.000	0.240	0.126	0.519	0.156	0.413	0.125	0.052	0.498	0.247
Cost	Initial cost	0.111	0.111	0.111	0.125	0.111	0.889	0.111	0.111	0.857	0.125	0.125	0.900	0.889
	Space heating cost	0.889	0.889	0.889	0.875	0.889	0.111	0.889	0.889	0.143	0.875	0.875	0.100	0.111
Environmetal impacts	GWP	0.333	0.667	0.250	0.250	0.750	0.750	0.125	0.125	0.000	0.125	0.333	0.000	0.000
	Energy demand	0.667	0.333	0.750	0.750	0.250	0.250	0.875	0.875	0.000	0.875	0.667	0.000	0.000
Hygrothemal performance	Moisture control	0.082	0.070	0.539	0.557	0.259	0.625	0.000	0.000	0.651	0.241	0.251	0.768	0.758
	R-value	0.575	0.350	0.297	0.320	0.703	0.304	0.875	0.875	0.249	0.715	0.702	0.152	0.163
	Thermal mass	0.343	0.580	0.164	0.123	0.038	0.072	0.125	0.125	0.100	0.044	0.046	0.079	0.079
Well-being	Aesthetics	0.125	0.125	0.125	0.125	0.125	0.000	0.000	0.000	0.143	0.125	0.000	0.000	0.000
	Health aspects	0.875	0.875	0.875	0.875	0.875	0.000	0.000	0.000	0.857	0.875	0.000	0.000	0.000

In this regard, the super-matrix comprises nine sub-criteria and four alternatives. The sub-criteria are placed in both row and column which includes initial cost, space heating cost, global warming potential, total energy, moisture control, R-value, thermal mass, aesthetics, and health aspects. The alternatives are the ICFs, PICP, WC, and WW which are located in the first four row and columns elements of super-matrix.

In order to obtain a relevant valid result, the super-matrix is transformed in accordance with ANP decision model. In step 2.1 the normalized cluster matrix was constructed. These numbers are multiplied by corresponding elements in the super-matrix, the purpose of this multiplication is to take into account the influences of the main criteria on the overall decision. To put it in simple words, criteria priorities vary based on their importance, for instance, well-being has higher priority in comparison with cost, it means in order to achieve a sufficient well-being in a building we should allocate resource (cost) to meet our needs. In the other words, from decision maker perspective that was obtained through survey the well-being has higher preference than cost. All these result are shown in Table 32 as a prioritized super-matrix respect to main criteria preferences.

Table 32 prioritized super-matrix

Cluster Node Labels		Alternatives				Cost		Environmetal		Hygrothemal performance			Well-being	
		ICFs	PICP	WC	WW	Initial cost	Space heating cost	GWP	Energy demand	Moisture control	R-value	Thermal mass	Aesthetics	Health aspects
Alternatives	ICFs	0.000	0.000	0.000	0.000	0.004	0.012	0.006	0.014	0.004	0.016	0.013	0.015	0.042
	PICp	0.000	0.000	0.000	0.000	0.009	0.007	0.015	0.030	0.002	0.008	0.013	0.006	0.012
	WC	0.000	0.000	0.000	0.000	0.006	0.002	0.006	0.003	0.013	0.004	0.003	0.045	0.046
	WW	0.000	0.000	0.000	0.000	0.006	0.003	0.029	0.009	0.013	0.004	0.002	0.066	0.033
Cost	Initial cost	0.015	0.015	0.015	0.017	0.005	0.043	0.003	0.003	0.022	0.003	0.003	0.068	0.067
	Space heating cost	0.119	0.119	0.119	0.117	0.043	0.005	0.025	0.025	0.004	0.023	0.023	0.008	0.008
Environmetal impacts	GWP	0.067	0.133	0.050	0.050	0.220	0.220	0.021	0.021	0.000	0.039	0.105	0.000	0.000
	Energy demand	0.133	0.067	0.150	0.150	0.073	0.073	0.146	0.146	0.000	0.275	0.209	0.000	0.000
Hygrothemal performance	Moisture control	0.027	0.023	0.180	0.186	0.076	0.000	0.000	0.000	0.102	0.038	0.039	0.101	0.100
	R-value	0.192	0.117	0.099	0.107	0.206	0.089	0.073	0.073	0.039	0.112	0.110	0.020	0.022
	Thermal mass	0.114	0.193	0.055	0.041	0.011	0.021	0.010	0.010	0.016	0.007	0.007	0.010	0.010
Well-being	Aesthetics	0.033	0.033	0.033	0.033	0.043	0.000	0.000	0.000	0.067	0.059	0.000	0.000	0.000
	Health aspects	0.233	0.233	0.233	0.233	0.299	0.000	0.000	0.000	0.404	0.412	0.000	0.000	0.000

In the following step the super-matrix should be normalized as a columnar stochastic matrix. The normalization process is determined by dividing each element by the sum of all elements in the corresponding column. By doing so, the obtained new matrix is called “weighted super-matrix” which is illustrate in Table 33. The consistency ratio (CR) for this matrix is 0.06 which is less than 0.1 and consistence.

Table 33 Weighted super-matrix

Cluster Node Labels		Alternatives				Cost		Environmetal impacts		Hygrothemal performance			Well-being	
		ICFs	PICP	WC	WW	Initial cost	Space heating cost	GWP	Energy demand	Moisture control	R-value	Thermal mass	Aesthetics	Health aspects
Alternatives	ICFs	0.000	0.000	0.000	0.000	0.004	0.025	0.018	0.041	0.005	0.016	0.025	0.045	0.123
	PICp	0.000	0.000	0.000	0.000	0.009	0.016	0.045	0.092	0.002	0.008	0.025	0.018	0.034
	WC	0.000	0.000	0.000	0.000	0.006	0.004	0.018	0.009	0.019	0.004	0.006	0.133	0.135
	WW	0.000	0.000	0.000	0.000	0.006	0.006	0.087	0.026	0.019	0.004	0.003	0.193	0.096
Cost	Initial cost	0.016	0.016	0.016	0.018	0.005	0.090	0.009	0.009	0.033	0.003	0.006	0.200	0.197
	Space heating cost	0.127	0.127	0.127	0.125	0.043	0.011	0.075	0.075	0.005	0.023	0.043	0.022	0.025
Environmetal impacts	GWP	0.071	0.143	0.054	0.054	0.220	0.457	0.063	0.063	0.000	0.039	0.198	0.000	0.000
	Energy demand	0.143	0.072	0.161	0.161	0.073	0.152	0.442	0.442	0.000	0.275	0.395	0.000	0.000
Hygrothemal performance	Moisture control	0.029	0.025	0.193	0.200	0.076	0.000	0.000	0.000	0.148	0.038	0.074	0.299	0.294
	R-value	0.206	0.125	0.107	0.115	0.206	0.185	0.221	0.221	0.057	0.112	0.208	0.059	0.063
	Thermal mass	0.123	0.208	0.059	0.044	0.011	0.044	0.032	0.032	0.023	0.007	0.014	0.031	0.031
Well-being	Aesthetics	0.036	0.036	0.036	0.036	0.043	0.000	0.000	0.000	0.098	0.059	0.000	0.000	0.000
	Health aspects	0.251	0.251	0.251	0.251	0.299	0.000	0.000	0.000	0.585	0.412	0.000	0.000	0.000

After normalization, the weighted super-matrix is raised to a significantly large number until the weights converge and remain stable values. The reason of raising this matrix to power is to capture the transmission of influence along all possible-path of the super-matrix. In this case, by raising the weighted super-matrix to power of 200 in each row the weights converged to a stable value. This was done by R software that number 200 was obtained by trial and error. This matrix is called limited super-matrix which is presented in Table 34.

Table 34 limited super-matrix

		Alternatives				Cost		Environmetal impacts		Hygrothemal performance			Well-being	
		ICFs	PICP	WC	WW	Initial cost	Space	GWP	Energy	Moisture	R-value	Thermal	Aesthetics	Health
Alternatives	ICFs	0.055223	0.055293	0.055117	0.055108	0.055057	0.055063	0.056023	0.056034	0.054269	0.055063	0.055354	0.054689	0.054704
	PICp	0.048576	0.048637	0.048483	0.048475	0.048429	0.048435	0.049279	0.049289	0.047736	0.048435	0.048691	0.048106	0.048120
	WC	0.048321	0.048382	0.048228	0.048220	0.048175	0.048181	0.049020	0.049030	0.047486	0.048180	0.048435	0.047853	0.047867
	WW	0.054309	0.054377	0.054205	0.054195	0.054145	0.054152	0.055095	0.055106	0.053370	0.054151	0.054438	0.053784	0.053799
Cost	Initial cost	0.077361	0.077459	0.077213	0.077200	0.077128	0.077137	0.078482	0.078497	0.076024	0.077137	0.077545	0.076613	0.076634
	Space heating	0.077611	0.077709	0.077462	0.077449	0.077377	0.077386	0.078735	0.078750	0.076269	0.077386	0.077795	0.076860	0.076882
Environmetal impacts	GWP	0.115102	0.115247	0.114881	0.114861	0.114754	0.114768	0.116768	0.116792	0.113112	0.114768	0.115375	0.113988	0.114020
	Energy demand	0.316228	0.316627	0.315622	0.315568	0.315274	0.315313	0.320807	0.320872	0.310762	0.315310	0.316979	0.313169	0.313256
Hygrothemal performance	Moisture control	0.147479	0.147665	0.147196	0.147171	0.147034	0.147052	0.149614	0.149644	0.144930	0.147051	0.147829	0.146052	0.146093
	R-value	0.215982	0.216254	0.215568	0.215531	0.215330	0.215357	0.219109	0.219153	0.212249	0.215355	0.216495	0.213893	0.213952
	Thermal mass	0.054269	0.054338	0.054165	0.054156	0.054105	0.054112	0.055055	0.055066	0.053331	0.054112	0.054398	0.053744	0.053759
Well-being	Aesthetics	0.037734	0.037781	0.037661	0.037655	0.037620	0.037625	0.038280	0.038288	0.037082	0.037624	0.037823	0.037369	0.037379
	Health aspects	0.249777	0.250092	0.249299	0.249256	0.249024	0.249054	0.253394	0.253445	0.245460	0.249052	0.250370	0.247361	0.247430

4.3.4.3 Final priorities of alternatives

Step4: Final step somehow leads us to determine the best alternative; however this determination needs to be interpreted by a decision maker to prioritize alternatives. In this case, decision model is a network of final matrix which is obtained by raising it to power of 200. The first four rows of the first column are selected. These four numbers are 0.055223, 0.048576, 048321, and 0.054309 corresponding to ICFs, PICP, WC, and WW, respectively. Ranking these numbers based on their values the final priorities of the alternative are 27%, 26%, 24%, and 23%, corresponding to ICFs, WW, PICP, and WC, respectively. It means the ICFs is the best option; the next recommended alternative is WW. These prioritizations are presented in Table 35. In this analysis, there were slight fractions between sub-criteria evaluations, approximately less than 10%. These small variations through super-matrix transformation led to obtain a close ranking of final results.

Table 35 final priority of scenarios

27 %	ICFs
24 %	PICP
23 %	WC
26 %	WW

4.3.4.4 Sensitivity analysis

The sensitivity analysis is performed in order to determine if the criteria weights change, then, how outcomes are robust in the ANP method. In addition, this sensitivity analysis would help to better understand of choosing exterior walls based on criteria. In this sense, several criteria are chosen to change their weights and then check the priority of alternatives. These criteria are those that would change with experts' opinion of four main criteria such as hygrothermal, LCC, LCA, and well-being as well as health aspects and aesthetics with regard to alternatives.

Table 36 shows the main criteria weight changes. These various weights were performed in five trials in order to check the final outcomes of alternative priorities. For example, by increasing the weight of cost from 5 to 40% the weights of other criteria would vary and the outcome of alternative prioritization is the same but with different percentages. We consider five different types of weighting to take into account the range of variable results for analysis. These outcomes are shown in alternative priorities in the last column. It can be seen that the final results indicate that ICFs is still the best option follows by WC, PICP, and WW that are as same as the previous outcome of actual calculation in section 4.3.4.3. In this case, there was not a significant change by using this type of sensitivity analysis.

Table 36 sensitivity analysis with respect to main criteria ranking

	Criteria	**Weight**	**Alternative priorities%**			
			ICFs	**PICP**	**WW**	**WC**
First trial	Hygrothermal	20	28	24	21	27
	Cost	15				
	environmental impacts	15				
	Well-being aspects	50				
Second trial	Hygrothermal	15	27	24	23	26
	Cost	25				
	environmental impacts	30				
	Well-being aspects	30				
Third trial	Hygrothermal	10	29	23	21	27
	Cost	30				
	environmental impacts	15				
	Well-being aspects	45				
Fourth trial	Hygrothermal	30	26.5	24.5	24	25
	Cost	20				
	environmental impacts	20				
	Well-being aspects	30				
Fifth trial	Hygrothermal	20	26.5	24	23.5	26
	Cost	20				
	environmental impacts	30				
	Well-being aspects	30				

Second sensitivity analysis was carried out on alternatives with respect to health and aesthetics aspects. These comparisons of alternative with respect to health and aesthetic were performed based on experts' judgments. It is assumed that theses pairwise comparisons can change, and then three trails are recalculated. The final result proved that the ANP method in this study is somehow robust. Table 37 illustrates this sensitivity analysis. It was observed that the final outcomes do not changing in terms of the final ranking.

Table 37 sensitivity analysis of alternatives with respect to well-being aspects

	Alternatives	**Weight respect to aesthetics**	**Weight respect to health aspect**	**Alternative priorities%**			
				ICFs	**PICP**	**WW**	**WC**
First trial	ICFs	20	20	27	23.5	23	26.5
	PICP	15	15				
	WC	30	30				
	WW	35	35				
Second trial	ICFs	25	25	28	22.5	22.5	27
	PICP	10	15				
	WC	25	20				
	WW	40	40				
Third trial	ICFs	35	40	28	24	22	26
	PICP	15	15				
	WC	25	15				
	WW	25	30				

Therefore, according to this sensitivity analysis, it can be observed that the prioritization of the alternatives does not depend on small variations in weighted super-matrix.

5 Discussions

5.1 Results Analysis

There were two main reasons why we have chosen the particular criteria of well-being, hygrothermal performance, cost, and environmental impact to evaluate the performance of exterior walls. First, we need to achieve space heating load reduction and durability improvement, both of which are major considerations for exterior walls in cold climate regions like Canada. Accordingly, we should take into account the types of wall assemblies that control heat, air, and moisture efficiently. These requirements lead us to construct an exterior wall assembly with sophisticated building materials as well as proper interface of wall with other elements in the building envelope. Undoubtedly, these sophisticated building materials lead to increase in the initial cost of construction phase as well as higher environmental impacts due to an increase in building material quantities. Regardless of the benefit of a reduction in space heating, there might be some undesirable consequences including an overall cost increase, a wider environmental footprint, impact on occupants' comfort, and moisture problems over the entire life span of a building. That is the second reason of why in this study we considered those main criteria in order to evaluate these consequences leading to the ranking of the proposed exterior walls.

In this study, we were dealing with nine sub-criteria that they can be divided into two categories: measurable and non-measurable. The former was obtained through calculations or computer modelling, while the latter was based on expert opinions obtained through interview survey. Measurable sub-criteria include R-value, thermal mass, and moisture control, and initial cost, space heating cost, GWP, and total energy demand. On the other hand, non-measurable sub-criteria include health aspects, aesthetics, and all main criteria importance with respect to each other as presented in Figure 32 where these were outcome of expert's judgment regarding of preferences of main criteria on choosing an exterior wall. Figure 33 presents the overall outcome of experts' opinion about four scenarios in terms of well-being aspects (health and aesthetics). It can be seen in Figure 33 that insulated concrete technology, ICFs and PICP, are not as aesthetic as wood-frame houses. On the other hand, these insulated concrete forms (ICFs) have nearly the same health aspects as wood-frame walls, however, PICP accounts for the lowest health aspects among all alternatives because it does not control moisture properly in comparison with other exterior walls.

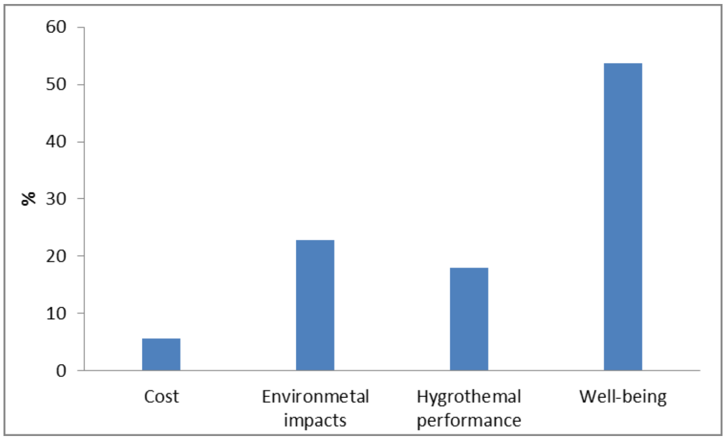


Figure 32 outcome of expert's judgment of preferences of main criteria

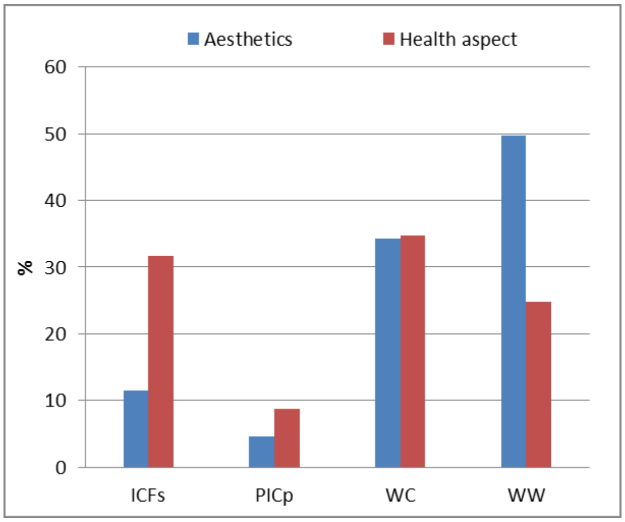


Figure 33 overall outcome of experts' opinion of well-being aspects

Turning to measurable criteria of cost, from initial cost, PICP stood at lower end of the price spectrum in contrast to other alternatives as discussed in section 4.3.2.1 and Figure 28 . In terms of space heating costs over the entire life span, it was observed that insulated concrete technologies consumed less energy on space heating because of controlling heat losses slightly better than wood-frame house, where they saved on energy costs by nearly $400,000 as compared to wood-frame houses as shown in Figure 28 over a 65 year period.

In terms of environmental impacts, over the pre-use phase, a wood-frame house with a main structure of wood (WW) had the lowest GWP and energy demand than other alternatives. This can be explained by the fact that it contained less concrete and steel in its elements whereas ICFs, PICP, and WC required approximately 80, 70, and 70 cubic meters of concrete respectively, where one ton of cement emits 900 kg of CO2 into the air [95]. However, over the operation phase of scenarios ICFs and PICP consumed nearly 10% less energy on space heating than WW and WC. However, this 10% does not affect the GWP as in Montreal it was assumed that all houses rely on electricity generated from hydro-power [73] .

Moving to hygrothermal performance, this thesis evaluated three areas: (1) R-value, heat loss or energy consumption on space heating. (2) Moisture control and (3) thermal mass. All calculations and comparisons in section 4.3.1 indicated that insulated concrete wall technologies have higher R-values and less heat loss in comparison with other alternatives. The annual space heating were 9.2, 9.51, 10.36, and 10.55 (1000KWh) for ICFs, PICP, WW, and WC houses, respectively, as illustrated in Figure 26. The main reason that insulated concrete technologies acted better on space thermal load is due to their higher thermal mass as well as lower thermal bridging that was already computed in Table 16. In terms of moisture control, all scenarios were simulated via WUFi in order to determine condensation risk, moisture content, dry out potential, and mold growth. The overall outcome of evaluations identified that wood-frame houses control moisture slightly better than ICFs and PICP because they have a higher drying out potential as compared to concrete.

All of the above comparisons and calculations made it a challenge to choose the best alternative as presented in Table 26. In this regard, the ANP method was applied to overcome this complexity, indeed, how the ANP method helped us to make a decision is discussed as following (however it was already elaborated on in section 4.3.4 where ANP method calculations were carried out). Firstly, its capability to define the interaction between criteria and sub-criteria (elements) provide an easy way to create a structure of decision-making problems in a network as shown in Figure 31. Secondly, we were dealing with two types of criteria, tangible and intangible. The ANP method has this feature to take into account both criteria in terms of a pairwise comparison between each two elements, that all these were performed based on absolute number of importance which was summarized in section 4.3.4.2, for instance, super matrix in Table 31 is the consequences of these pairwise comparisons among elements by taking into consideration of all possible interactions between sub-criteria. Thirdly, this study performed nearly 160 pairwise comparisons, which controlling of consistency according to consistency ratio made it acceptable that in this case was 0.06 where it is less than 0.1 according to fundamental guide lines of the ANP method. Lastly, by raising the weighted super matrix to a large number, the priority of alternative was obtained, where ICFs was the best choice as indicated in Table 35. As such, our recommendation is first go for IFCs, and then WC, IPCP and WW.

5.2 Limitations

Through this study there were some limitations or assumptions which can be divided into two categories including methodology and simulation limitations. In terms of methodology limitations, it can be said that LCA and LCC analysis are under a basic assumption that we can use the available data (existing and historical) to formulate future predictions. Due to unforeseen uncertainties and variations, historical data might not be able to provide the best estimates about the future conditions of building components. This is considered as a limitation for the proposed methods. In the literature reviews, such limitations are mentioned (referring to sections 2.2 and 2.3).

All scenarios in this study were modeled using various software programs, whereas actual house performance results would be variable. However, knowing the inputs and initial conditions, we could understand and interpret the obtained outcomes. In this sense, to reduce the extent of the variability of inputs and initial conditions, we did not considered deterioration of materials over long-term run, air movement modeling through crack and interface of assembly, maintenance and repair of these alternatives on use phase, change on energy price in long-term, change on case studies maintain energy efficiency performance over long-run, and solar radiation influences on mold growth in exterior walls. The proposed methodology will serve as a first step towards understanding the main conditions and issues in ranking of exterior walls based on the set of most influencing criteria. The above limitations could be explored as future avenues of research as we suggest in the conclusions section.

6 Conclusions

6.1 Summary

This study provided a framework for decision making on choosing an exterior wall among alternatives using the ANP method. We employed this framework in a set of typical residential buildings in Montreal, Canada. This research was initially motivated by ASHRAE Advanced Energy Design Guides in which it advocates the reduction of the thermal energy load in buildings by adopting traditional design approaches. Thus, three alternative exterior walls were chosen: insulated concrete forms (ICF), insulated pre-cast concrete panel (PICP), and wood-frame. The reason for studying these three alternative walls was to determine the impacts of thermal mass as well as thermal bridging on space heating loads. Most previous studies have emphasized that the combination of thermal mass with proper insulation in exterior walls could lead to higher energy efficiency in buildings in terms of space heating or cooling load reduction. Furthermore, two Canadian energy efficiency initiatives, such as Advanced House Program and Net-Zero Energy Home Coalition, further motivated us to study traditional exterior walls (wood-frame) in comparison with feasible technologies such as insulated concrete walls in order to achieve a high energy efficient house.

The three exterior walls were made using various insulation materials but the main goal is to meet the building code of Canada in Montreal in terms of mandated R-values on exterior walls. Therefore, these three alternative walls were assembled in accordance with the ASHRAE standard and building code. And then, the consequences of applying these walls in buildings was evaluated, in which, for the purpose of this evaluation, four case studies (scenarios) were introduced and simulated by various software programs such as eQUEST, WUFi, Simapro, and THERM. The outcomes of those simulations as well as actual calculations were compared in order to select the best option. This proved to be a complex problem due to the four main criteria (well-being aspects, hygrothermal performance, LCC, and LCA) with nine sub-criteria including initial cost, space heating cost, GWP, total energy consumption, health aspects, aesthetics, thermal resistance, thermal mass, and moisture control. All of those criteria were analysed over the entire life cycle of a house including in each phase (pre-use, use, and demolition). Therefore, by utilizing a MCDM approach such as the ANP method, this complexity was solved in a super matrix of 13*13 orders. The final result of prioritizing the alternatives were 27%, 26%, 24%, and 23%, corresponding with ICFs, WW, PICP, and WC, respectively. This type of assessment provided an integrated framework that can assist decision makers in the design stage to overcome complexity. Moreover, this approach can be employed for the evaluation of any building materials or assemblies subject to modification of the criteria.

The contribution of this study, as compared to similar studies in this area, is that it integrates four main criteria of hygrothermal, LCC, LCA, and well-being aspects by considering their interrelationship over a long term using the ANP method. Moreover, we could confirm that the combination of thermal mass and insulation material in exterior walls could lead to energy savings, resulting in less GWP and lower space heating cost.

6.2 Future works

In terms of future work, through this study, we found several new challenges that can be proposed as future works as followings:

First, deterioration of insulation material over a long-term run can create variations in the outcomes. In order to evaluate deterioration, we need historical data along with laboratory tests.

The extent of maintenance and repair requirements for these alternatives (exterior walls) during their service life could affect the decision making in the preliminary design stage. Thus, a potential future work will be to introduce a framework on consequences of maintenance for exterior walls over the long term on their cost as well as durability.

In addition, solar radiation has influences on mould growth in exterior walls as an increased temperature provides conditions for micro-organism growth. On the other hand, it can drop the RH%, and thus, the lack of moisture will be a positive factor in preventing mould growth. This will be subject to orientation and geographical location of the building.

This study focused on three exterior walls. This framework could be adopted to evaluate alternative windows in buildings based on the size, type of glazing, shading, and other relevant aspects.

Another area for future work would be to investigate and evaluate alternative types of cement in order to identify the more environmentally friendly options in terms of GWP.

Finally, in this study, we considered only electricity as the source of energy (from hydro-power) for space heating. A future research direction could be on consideration of other sources of energy such as natural gas, fossil fuel, renewable energy, and cogeneration, which will create variations in terms of cost and GWP.

7 References

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8 Appendices

8.1 Appendix-A (R-value and water vapor diffusion)

Calculation of thermal resistance and vapor barrier of three type exterior walls including Wood frame, Insulated Concrete Forms (ICF), and Insulated Pre-cast Concrete Panel (IPCP)

1- Calculation of Thermal resistance based on Parallel method: (all units are in SI system)

According to Building Code of Canada the thermal resistance in an exterior wall in Montreal should be as following in a new building:

R-value= 23 h.F.ft^2/BTU Or RSI-value=4.05 K.m^2/W R-value= 5.685 * RSI-value

Location	HDD	Wall R-value	Roof R-value	Fenestration R-value
Montreal	4000-4999 (region 6)	23	31	2.58

Based on this RSI=4.05 we can calculate the thickness and component of each assembly.

1-1-Wood frame

-Referring to table 1 chapter 26 of ASHRAE 2013, material conductivity (column 3 in Table 1)

-Initial thickness of insulating materials is assumed (colum2 in Table 1), if it does not meet the R-value, it will change later on second trial.

-Inside and outside air film thermal resistance are considered based on table 10 chapter 26 of ASHRAE 2013 which means for heat transfer through convection and radiation we use tables which recommended by ASHRAE.

-Assumption:

Outside temperature=-20°C (winter condition), RH= 60%

Inside temperature =+20° C, RH=40%

Heat transfer in one dimension (across plain wall) also in the case of thermal bridging it is considered in two dimensions.

-Heat flows through wood frame wall in three paths (1, 2 and 3) as shown below in figure 1 these paths depend on element conductivity.

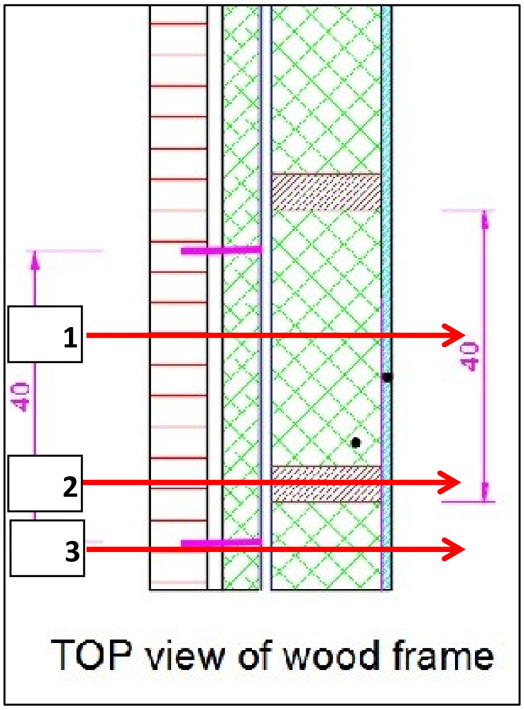


Figure 1

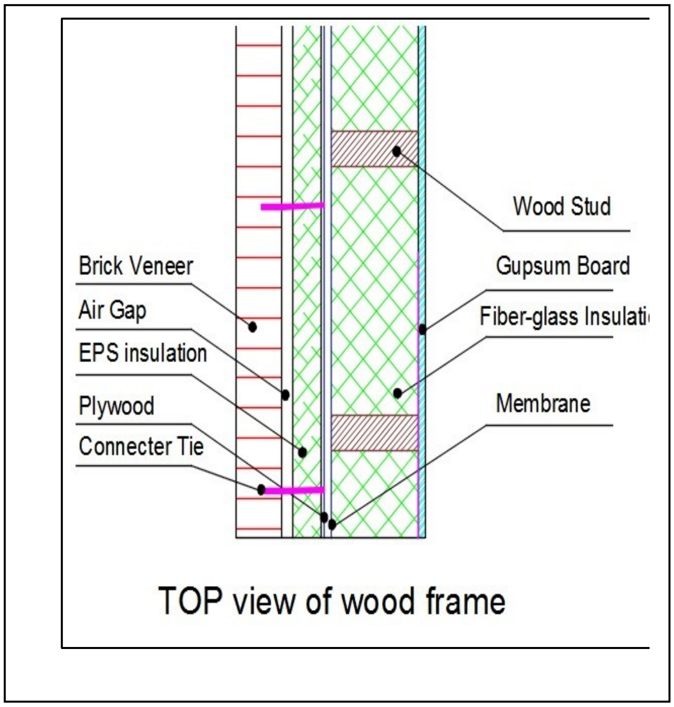


Figure2

Path 1:

$\mathbf{R}_{\text{Path1}} = \sum_{1}^{n} Ri$ = .029+.083+.5+1.215+.014+.14+2.7+.081+.12= 4.883 K.m^2/W See colum5 in table 1

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	W/m^2.K	m^2.K/W
Outside Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Air Gap	0.02		2	0.500
Exterior Insulation	0.04	0.033	0.825	1.215
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Insulation	0.15	0.046	0.307	2.700
gypsum Board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path1)				4.883

Table 1

Path 2:

Considering the heat-flow through wood stud the calculation is present in table 2.

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	$W/m^2.K$	$m^2.K/W$
Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Air Gap	0.02		2	0.500
Exterior Insulation	0.05	0.033	0.66	1.515
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Wood stud	0.15	0.16	1.067	0.938
gypsum Board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path2)				3.118

Table 2

R_{Path2}= 3.118 $K.m^2/W$

In table 2 the insulation inside cavity doesn't act, instead all heat flows through wood stud.

Path 3:

Heat flows through connecter ties. See table 3

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance (R-value)
	m	W/m.K	W/m2.K	m2.K/W
Air Film			34	0.029
Brick Veneer	0.1	1.21	12.1	0.083
Connecter tie	0.07	45.3	647.14	0.002
Membrane (Tyvek)	0.003	0.21	70	0.014
Plywood	0.013			0.140
Insulation	0.15	0.046	0.307	2.700
gypsum Board	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R (path3)				3.170

R_{Path3}= 3.17 K.m2/W Tabl

Overall R-value: Based on their area of each path the overall R-value can be computed as below:

$A=100*100 = 10000\ Cm^2$

$A_{stud}= 2*(5*100) =1000\ cm^2$ There are 2 stud in $1m^2$ (path2)

$A_{ties}= 9*(2*3) = 5.4\ cm^2$ There are 9 connecter ties in each $1m^2$ (path3)

$A_{plain} = 10000-(5.4+1000)= 8994.6\ cm^2$ (this is the plain wall area path 1)

$$U=\sum\frac{Ai}{A.Ri} = \frac{8994.6}{4.883*10000}+\frac{1000}{3.118*10000}+\frac{5.4}{3.17*10000} = 0.1735 + 0.0292 + 0.000170 = 0.216$$

$\frac{\mathbf{1}}{\mathbf{U}} = \mathbf{R}$ and the Overall R = 4.62 Km^2/W this is the RSI-value for wood frame by using 19cm insulation material see the figure 2 of wood frame wall and its components.

1-2- Insulated concrete forms (ICF)

Here, we consider the same assumption as above. Heat flows through ICFs in two paths, first through plain wall, and second through connecter ties which secure brick veneer to backup wall that in this case is concrete wall.

Path1: through the plain wall as shown in table 4.

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance
	m	W/m.K	W/m2.K	m2.K/W
Outside Air Film			34.000	0.029
Brick Veneer	0.1000	1.210	12.100	0.083
Air Gap	0.0200		2.000	0.500
Membrane (Tyvek)	0.003	0.21	70	0.014
Exterior Insulation	0.0600	0.033	0.550	1.818
Concrete	0.1500	2.000	13.333	0.075
Interior Insulation	0.0600	0.033	0.550	1.818
gypsum Board+ paint	0.013	0.16	12.308	0.081
Inside Air Film			8.300	0.120
R (path1)				4.539

Table4

Path2: By considering the connecter ties which act as a thermal bridge phenomenon

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance
	m	W/m.K	W/m2.K	m2.K/W
Outside Air Film			34.000	0.029
Brick Veneer	0.1000	1.210	12.100	0.083
Connecter tie	0.08	45.3	566.25	0.002
Concrete	0.1500	2.000	13.333	0.075
Interior Insulation	0.0600	0.033	0.550	1.818
gypsum Board+ paint	0.013	0.16	12.308	0.081
Inside Air Film			8.300	0.120
R (path2)				2.209

Table 5

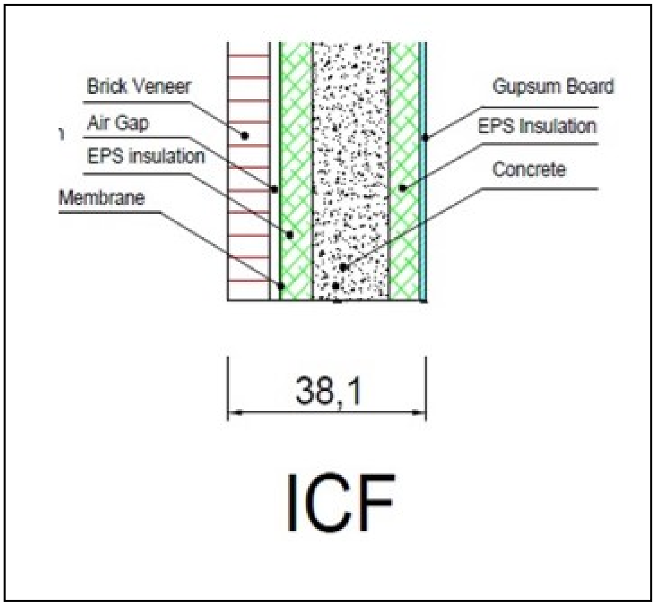


Figure 3

$$U=\sum \frac{Ai}{A.Ri} = \frac{9994.6}{4.539*10000} + \frac{5.4}{2.209*10000} = 0.2202 + 0.00024 = 0.22044$$

R= 4.536 Km^2/W overall R-value for ICF system

1-3- Insulated pre-cast concrete panel (IPCP):

Heat transfers through Insulated pre-cast concrete panel in plain wall as shown in table 6

column1	column2	column3	column4	column5
Wood Frame Component	Thickness	Conductivity	Conductance	Resistance
	m	W/m.K	W/m2.K	m2.K/W
Air Film			34	0.029
Exposed Concrete	0.08	1.6	20	0.050
Insulation + Water stop	0.1	0.025	0.25	4.000
Interior Concrete	0.15	1.6	10.667	0.094
Gypsum Board+ paint	0.013	0.16	12.308	0.081
Inside Air Film			8.3	0.120
R				4.375

Table 6

2- Temperature gradient through assemblies

Referring to page 25.7 ASHRAE 2013 the temperature drop through any layer of an assembly is proportional to its thermal resistance.

$$dt = \frac{Rj(ti-to)}{RT}$$

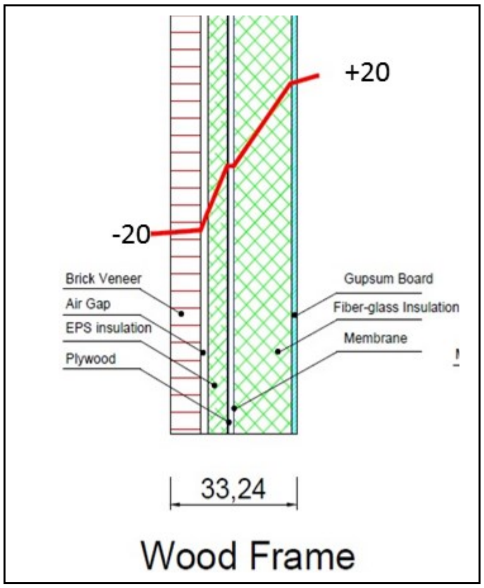
2-1- Temperature through wood frame layers

Table 7 shows the variation of temperature through wood frame assembly also figure 5 presents the profile.

Wood Frame Component	Thickness	DT	T
	M	$_o$c	$_o$c
Outside			-20.0
Air Film		0.255754	-19.7
Brick Veneer	0.1	0.718649	-19.0
Air Gap	0.02	4.347826	-14.7
Exterior Insulation	0.04	10.17391	-4.5
Membrane (Tyvek)	0.003	0.124224	-4.4
Plywood	0.013	1.217391	-3.2
Insulation	0.15	21.3913	18.2
gypsum Board	0.013	0.706522	18.9
Inside Air Film		1.047669	20.0
Inside			20.0

Table7

Figure 5



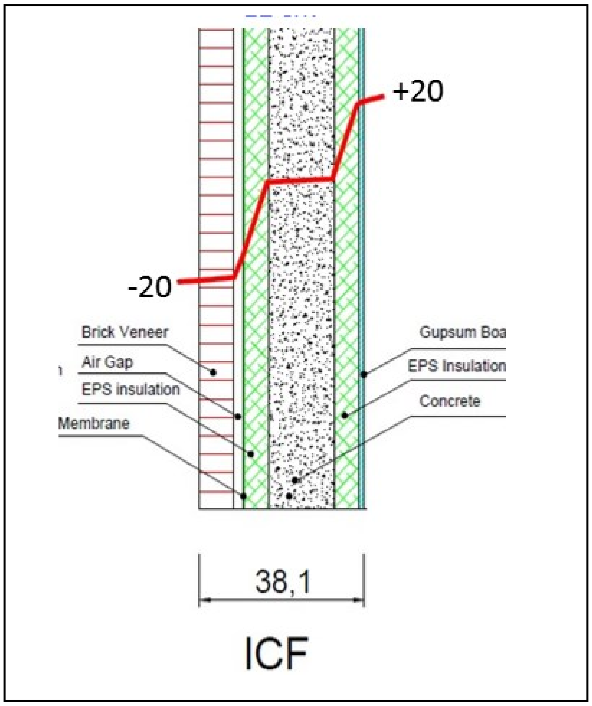
2-2- Temperature through ICF layers

The same method as mentioned before, illustrates in table 8 and figure 6 regard to temperature drop through ICFs assembly.

Table 8

Wood Frame Component	Thickness	DT	T
	M		
Outside			-20
Outside Air Film		0.26	-19.74
Brick Veneer	0.1000	0.73	-19.01
Air Gap	0.0200	4.41	-14.61
Membrane (Tyvek)	0.003	0.13	-14.48
Exterior Insulation	0.0600	16.02	1.54
Concrete	0.1500	0.66	2.20
Interior Insulation	0.0600	16.02	18.22
gypsum Borard+ paint	0.013	0.72	18.93
Inside Air Film		1.06	20.00
Inside			20.00

Figure 6



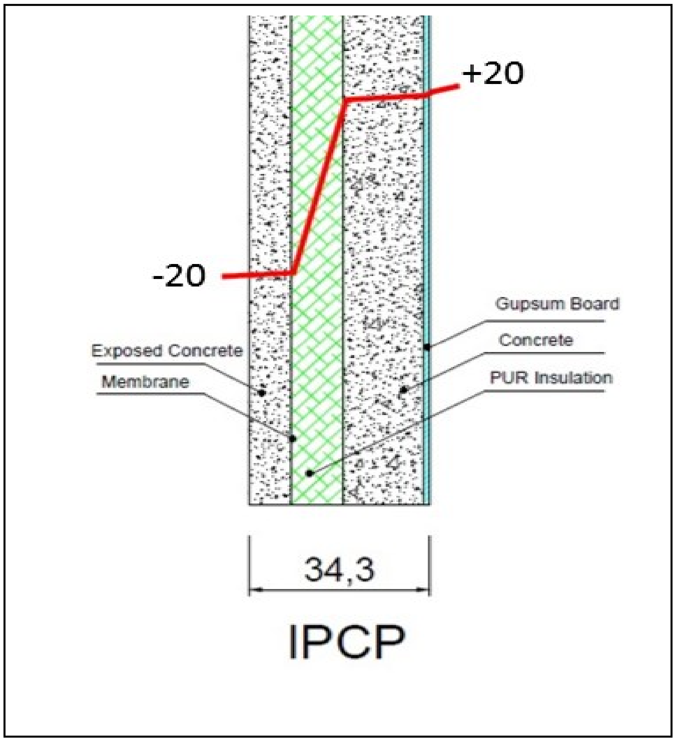
2-3- Temperature through IPCP layers

The same method as mentioned before would apply for IPCP assembly.

Table 9

Wood Frame Component	Thickness	DT	T
	M		
Outside			-20
Air Film		0.269	-19.7
Exposed Concrete	0.08	0.457	-19.3
Insulation + Water stop	0.1	36.530	17.3
Interior Concrete	0.15	0.856	18.1
gypsum Board+ paint	0.013	0.742	18.9
Inside Air Film		1.100	20.0
Inside			20.0

Figure7



3- Water Vapor resistance calculation through assemblies

- Fick's law of diffusion $$\frac{\dot{m}_A}{A} = -D\frac{\partial C_A}{\partial x}$$

where

D = proportionality constant–diffusion coefficient, m^2/s
$\dot{m}_A$ = mass flux per unit time, kg/s
C_A = mass concentration of component A per unit volume, kg/m^3

This equation applies for vapor diffusion because of vapor pressure differences between inside and outside of building; also the following equation is applicable for calculation of vapor transfer through assemblies.

$$W = \overline{\mu} A \theta \frac{(p_1 - p_2)}{l}$$

W = total mass of water vapour transmitted, ng
P = vapor pressure, Pa
— = vapor permeability of the material ng/s. m. Pa
θ = time, s
A = cross-section area of the flow path, m^2
l =length along the flow path, m

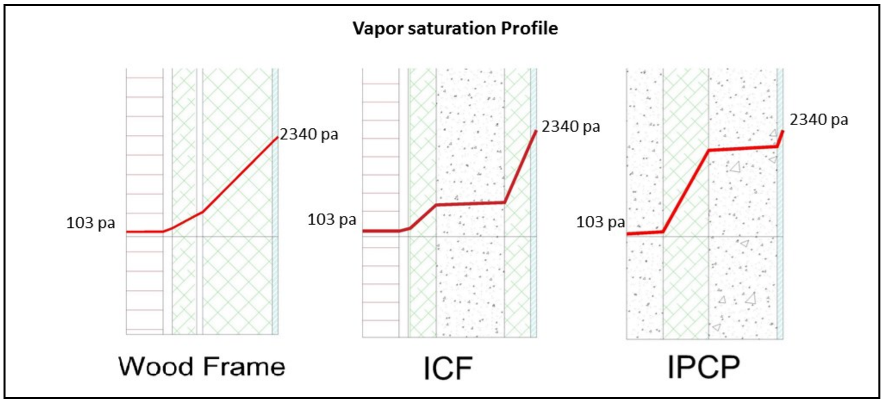
Table 5 in chapter 26 of ASHRAE 2013 shows the Vapor permeability of common building materials which these are shown in column 9 in all calculation tables.

We need more simplicity for our calculation so we are able to consider the following equation (vapor flux)

$\dot{w} = \frac{dp}{R}$ which R= $\frac{1}{\mu}$ so-called vapor Resistance and dp=(p_{in}-p_{out}) which P is water vapor pressure.

First it is needed to find saturation vapor pressure for each given temperature from table 3 on first chapter of ASHRAE 2013 (Thermodynamic properties of water at saturation) in this calculation we already computed the temperature gradient. The figure 8 shows the saturation capability of each wall which depends on Overall R-value and inside and outside temperature. See the column 9 in all tables in this calculation.

Figure 8



Assumption:

Outside condition: Temperature= -20°C, Relative Humidity (RH) = 60% and water vapor pressure equals to 62 pa (RH=$\frac{Pw}{Ps}$*100 , 0.60=pw/103 , and Pw=0.6*103= 62 pa it means P_{out}= 62pa)

Inside condition: Temperature= +20°C and, RH= 40% , the same calculation leads to P_{in}=936pa

3-1- Wood frame vapor transfer calculation

For avoiding condensation we need to know the saturation of Vapor pressure for each layer based on its temperature (column 9) as shown earlier in figure 8.

-First we consider all calculation without vapor barrier and then we will repeat the same approach by taking into account of existence of vapor retarder in the warmer side.

-Columns 10 to 12 in table 10 are the material properties in which related to vapor permeability from ASHRAE. Also vapor resistance is 1/presence for example:

For brick $R_{brick}=\frac{1}{51.2}$ = 0.019531 Pa.s.m^2/ng and so on.

-Total resistance for the assembly: R=$\sum Ri$ = 0.064891 Pa.s.m^2/ng

-According to Equation $\dot{w} = \frac{dp}{R}$ the overall vapor resistance is 0.064891 pa.s.m^2/ng that in column 13 in table 10 that vapor pressure drop can be computed for each component (layer). For instance:

$W_{8\text{-}1} = \frac{dp}{R} = \frac{(936-62)}{0.064891}$ = 13292 ng/s.m^2

Vapor pressure drop for each layer equals to R_i *$W_{8\text{-}1}$ for brick = 0.019531*13292= 263 pa and the same approach for other layers which are illustrated in column 13 in table 10.

-Column 14 in table 10 shows the water vapor pressure in each layer (vapor flows from inside with 936 pa towards outside with 62pa), for instance, vapor pressure after Gypsum board = 936-5= 931 and after insulation layer= 931-434=455

-Comparing P_{sat} and P_w of each surface if $P_w > P_{sat}$, it means there is condensation. Comparing the column 9 in table 10 and column 14 in order to find where there might be condensation that in all the red cells the water vapor pressure are more than saturation pressure which means there are condensation on surface#6, #5, #4, #3, #2, but these vapor pressures cannot be more than saturation, therefore we have to adjust them to saturation pressure.

Therefore, on surface #6 the initial vapor pressure is 498 which is greater than 476, by adjusting the P_w to 476 on surface #6, the column 15 and 16 in table 10 can be recalculated again by different vapor flux (w) as below:

$W_{6\text{-}8} = \frac{936-476}{0.000346}$ = 14139 ng/s.m^2

$W_{6\text{-}1} = \frac{476-62}{0.0645} = 12795$ ng/s.m^2

Based on these two new rates the vapor drop and vapor pressure on each layer can be easily computed as we done before,where the all result of calculation are shown in column 15 and 16 in table 10.

-In the new calculation in column 16in table 10 there are condensation on surfaces #5, #4, #3 and #2 which we need to adjust vapor pressure on surface #5 to 415 pa which will be repeated the same calculation as before.

$W_{6\text{-}5} = \frac{476-415}{0.004075} = 14968$ ng/s.m^2

$W_{5\text{-}1} = \frac{415-62}{0.0323} = 12795$ ng/s.m^2

The new results are shown in columns 16 and 18 in table 10.

-The same approach will apply for each surface that condensation may occur, that all the green cells in table 10 are vapor pressures on the surface of materials through assembly. The figure 9 presents the vapor diffusion through Wood frame.

Figure 9

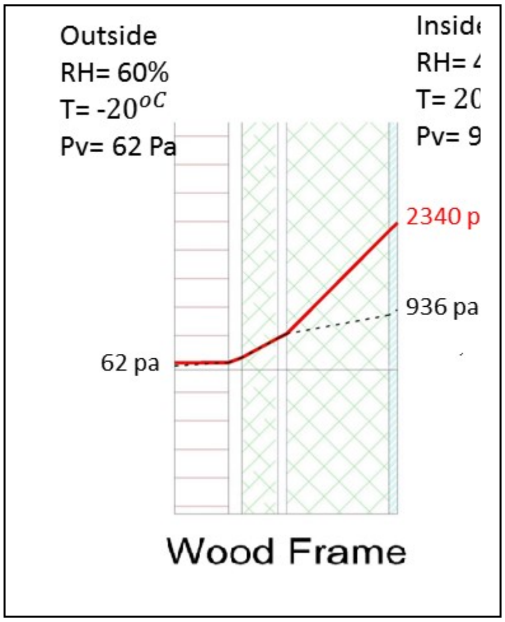
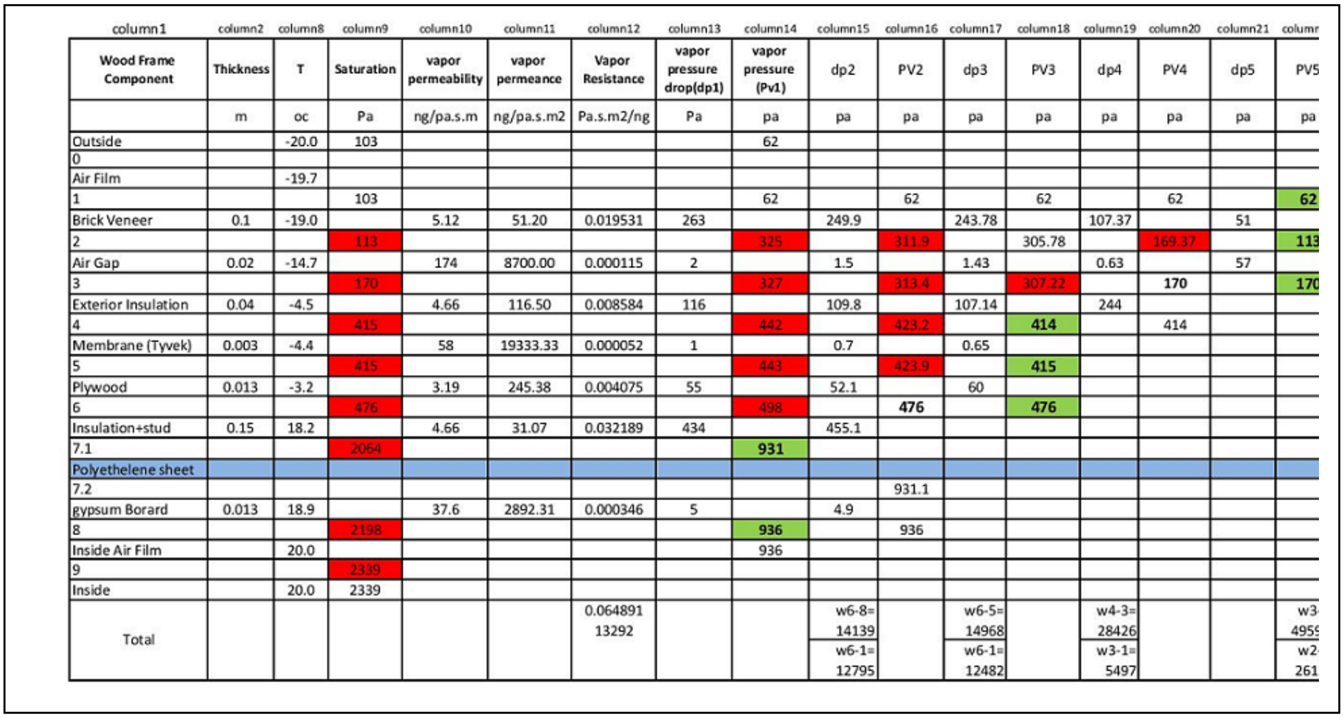


Table 10 . Calculation of wood frame in terms of vapor transfer without vapor



column1	column2	column8	column9	column10	column11	column12	column13	column14	column15	column16	column17	column18	column19	column20	column21	colum
Wood Frame Component	Thickness	T	Saturation	vapor permeability	vapor permeance	Vapor Resistance	vapor pressure drop(dp1)	vapor pressure (Pv1)	dp2	PV2	dp3	PV3	dp4	PV4	dp5	PV5
	m	oc	Pa	ng/pa.s.m	ng/pa.s.m2	Pa.s.m2/ng	Pa	pa	pa	pa	pa	pa	pa	pa	pa	pa
Outside		-20.0	103					62								
0																
Air Film		-19.7														
1			103					62		62		62		62		62
Brick Veneer	0.1	-19.0		5.12	51.20	0.019531	263		249.9		243.78		107.37		51	
2			113					325		311.9		305.78		169.37		113
Air Gap	0.02	-14.7		174	8700.00	0.000115	2		1.5		1.43		0.63		57	
3			170					327		313.4		307.22		170		170
Exterior Insulation	0.04	-4.5		4.66	116.50	0.008584	116		109.8		107.14		244			
4			415					442		423.2		414		414		
Membrane (Tyvek)	0.003	-4.4		58	19333.33	0.000052	1		0.7		0.65					
5			415					443		423.9		415				
Plywood	0.013	-3.2		3.19	245.38	0.004075	55		52.1		60					
6			476					498		476		476				
Insulation+stud	0.15	18.2		4.66	31.07	0.032189	434		455.1							
7.1			2064					931								
Polyethelene sheet																
7.2										931.1						
gypsum Borard	0.013	18.9		37.6	2892.31	0.000346	5		4.9							
8			2198					936		936						
Inside Air Film		20.0						936								
9			2339													
Inside		20.0	2339													
Total						0.064891 13292			w6-8= 14139 w6-1= 12795		w6-5= 14968 w6-1= 12482		w4-3= 28426 w3-1= 5497			w3 495 w2 261

-By applying polyethylene sheet as a vapor retarder the calculation will be as following:

- The permeance of Polyethylene sheet μ=0.2 ng/pa.s.m^2 and the vapor resistance R= 1/0.2 = 5 Pa.s.m2/ng

- This sheet is installed on the warmer side of assembly after the Gypsum board.

R= 5+0.064891 = 5.064891 pa.sm2/ng This new Rp so-called the overall vapor resistance of assembly with vapor barrier.

$$W_{8\text{-}1} = \frac{936-62}{5.064891} = 172.56 \text{ ng/s.m2P}$$

dp= w*R

$P_{w\#7}$ = 172.56* 0.000346= 0.06 pa

$P_{w\#6}$ = 172.56* 5 = 826.87 pa and all the rest of surface vapor pressure drop have been calculated on column23 in table 11

-The column 24 in table 11 shows the vapor pressure on each surface

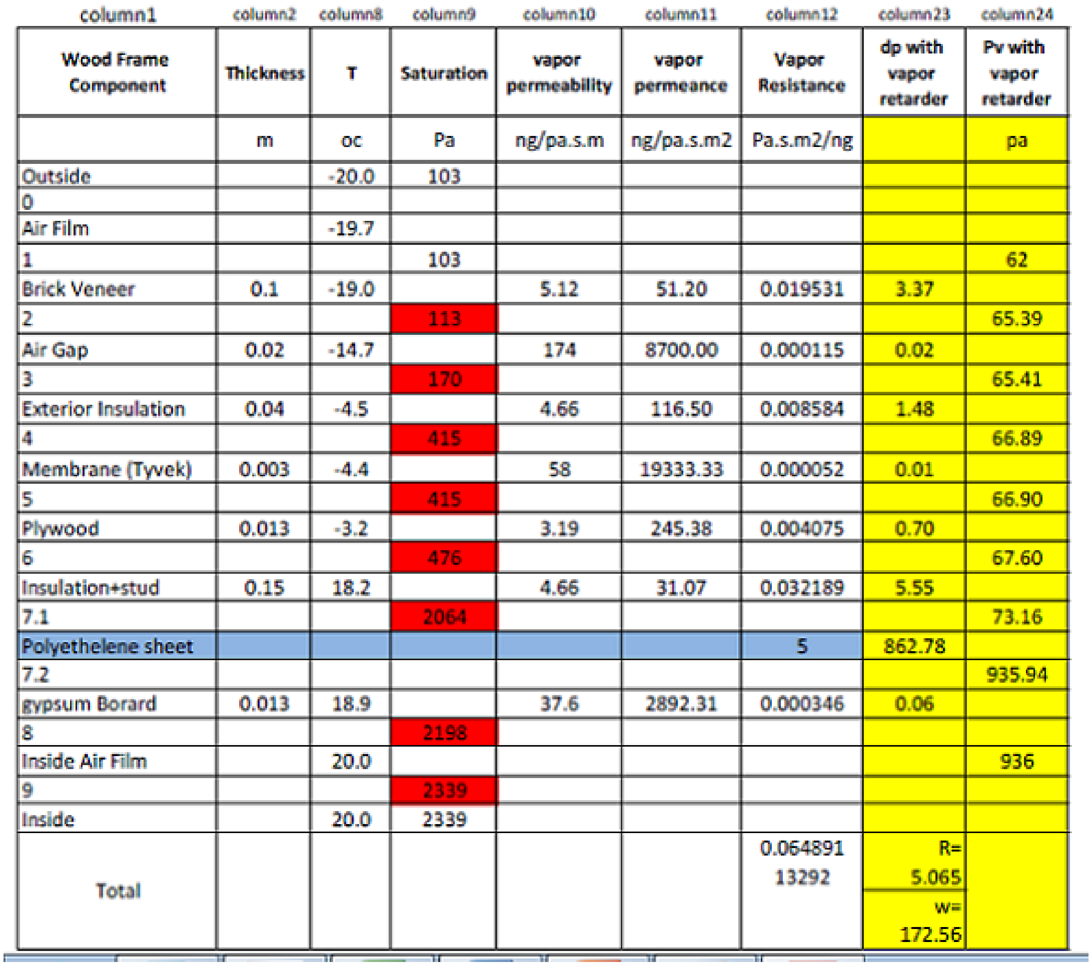
Surface #8= 936

Surface #7= 936 - 0.06 = 935.54

Surface #6 = 935.54 – 826.87 = 73.16 pa

Other surfaces are computed the same way which are presented in column 24 in table 11.

Table 11. Calculation of wood frame in terms of vapor transfer with vapor retarder



column1	column2	column8	column9	column10	column11	column12	column23	column24
Wood Frame Component	**Thickness**	**T**	**Saturation**	**vapor permeability**	**vapor permeance**	**Vapor Resistance**	**dp with vapor retarder**	**Pv with vapor retarder**
	m	oc	Pa	ng/pa.s.m	ng/pa.s.m2	Pa.s.m2/ng		pa
Outside		-20.0	103					
0								
Air Film		-19.7						
1			103					62
Brick Veneer	0.1	-19.0		5.12	51.20	0.019531	3.37	
2			113					65.39
Air Gap	0.02	-14.7		174	8700.00	0.000115	0.02	
3			170					65.41
Exterior Insulation	0.04	-4.5		4.66	116.50	0.008584	1.48	
4			415					66.89
Membrane (Tyvek)	0.003	-4.4		58	19333.33	0.000052	0.01	
5			415					66.90
Plywood	0.013	-3.2		3.19	245.38	0.004075	0.70	
6			476					67.60
Insulation+stud	0.15	18.2		4.66	31.07	0.032189	5.55	
7.1			2064					73.16
Polyethelene sheet						5	862.78	
7.2								935.94
gypsum Borard	0.013	18.9		37.6	2892.31	0.000346	0.06	
8			2198					
Inside Air Film		20.0						936
9			2339					
Inside		20.0	2339					
Total						0.064891 13292	R= 5.065 w= 172.56	

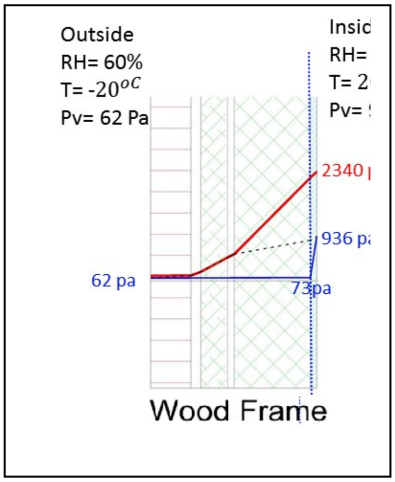


Figure 10. Applying vapor retarder in warmer side

3-2- Water vapor transfer through ICFs wall

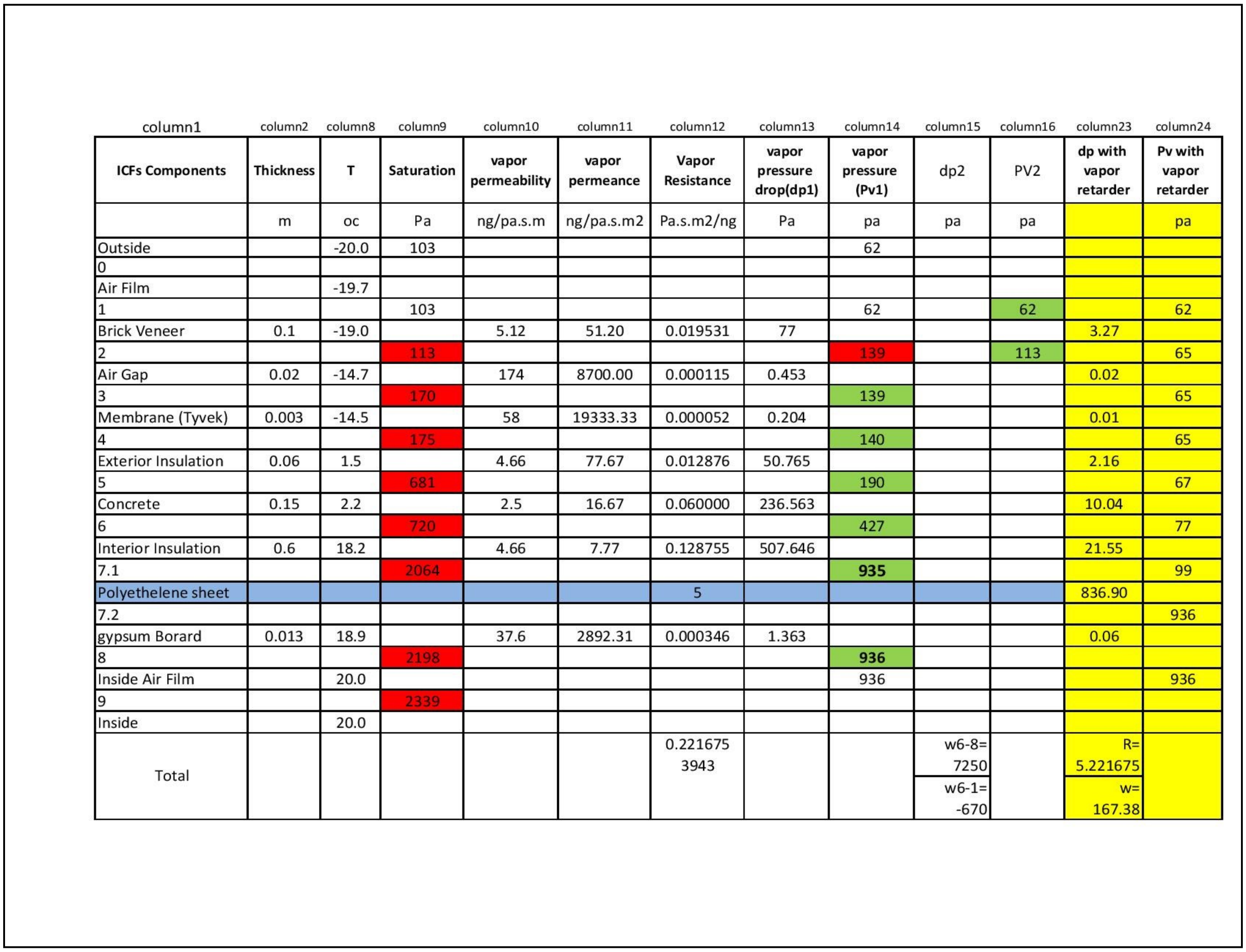
Table 12 was calculated exactly as same as wood frame.

It is clear that in this case condensation occurs on the outer side of wall.

-The yellow par is when we apply vapor retarder (polyethylene sheet) with R=5 pa.sm2/ng

-Initial calculation is done first and then in column14 in table 12 there is a condensation on air gap so by adjusting that cell with green color would be the vapor pressure on surface.

Table 12. Calculation of ICFs assembly in terms of vapor transfer without and with vapor retarder

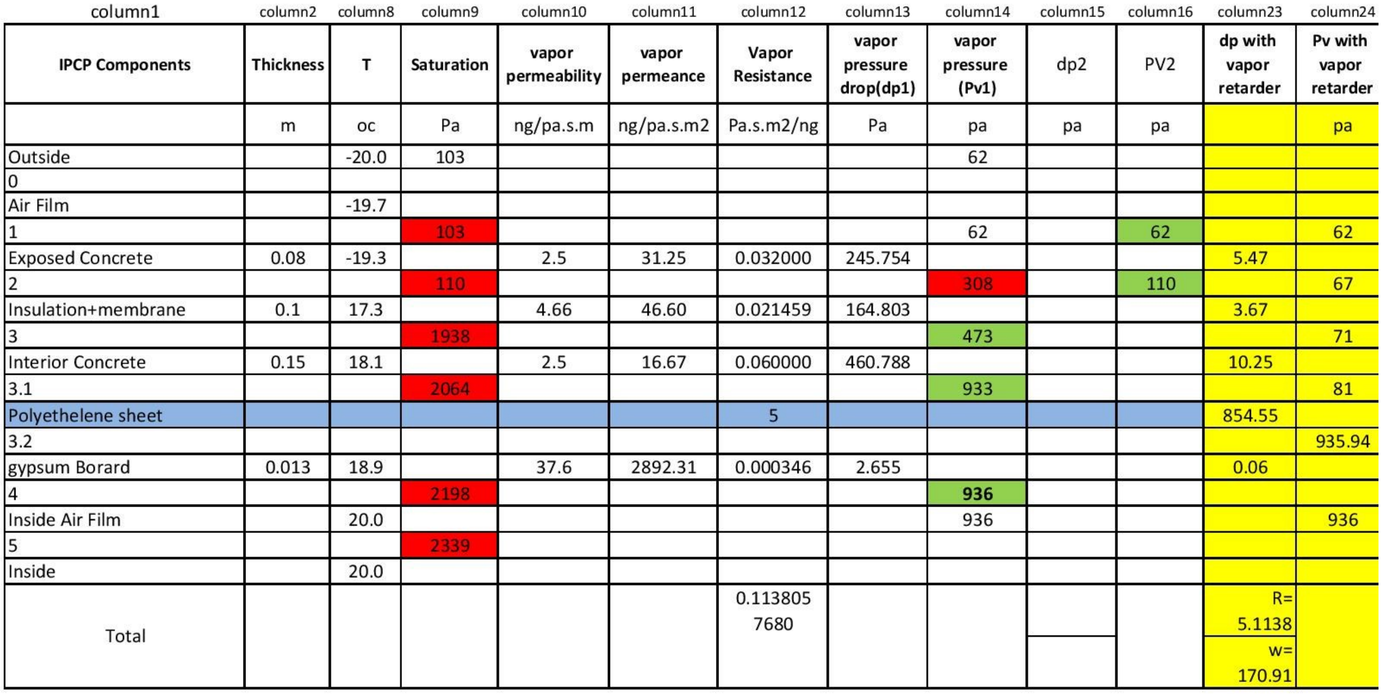


column1	column2	column8	column9	column10	column11	column12	column13	column14	column15	column16	column23	column24
ICFs Components	**Thickness**	**T**	**Saturation**	**vapor permeability**	**vapor permeance**	**Vapor Resistance**	**vapor pressure drop(dp1)**	**vapor pressure (Pv1)**	dp2	PV2	**dp with vapor retarder**	**Pv with vapor retarder**
	m	oc	Pa	ng/pa.s.m	ng/pa.s.m2	Pa.s.m2/ng	Pa	pa	pa	pa		pa
Outside		-20.0	103					62				
0												
Air Film		-19.7										
1			103					62		62		62
Brick Veneer	0.1	-19.0		5.12	51.20	0.019531	77				3.27	
2			113					139		113		65
Air Gap	0.02	-14.7		174	8700.00	0.000115	0.453				0.02	
3			170					139				65
Membrane (Tyvek)	0.003	-14.5		58	19333.33	0.000052	0.204				0.01	
4			175					140				65
Exterior Insulation	0.06	1.5		4.66	77.67	0.012876	50.765				2.16	
5			681					190				67
Concrete	0.15	2.2		2.5	16.67	0.060000	236.563				10.04	
6			720					427				77
Interior Insulation	0.6	18.2		4.66	7.77	0.128755	507.646				21.55	
7.1			2064					**935**				99
Polyethelene sheet						5					836.90	
7.2												936
gypsum Borard	0.013	18.9		37.6	2892.31	0.000346	1.363				0.06	
8			2198					**936**				
Inside Air Film		20.0						936				936
9			2339									
Inside		20.0										
Total						0.2216753943			w6-8= 7250 w6-1= -670		R= 5.221675 w= 167.38	

3-2- Water vapor transfer through Insulated Pre-cast Concrete Panel wall

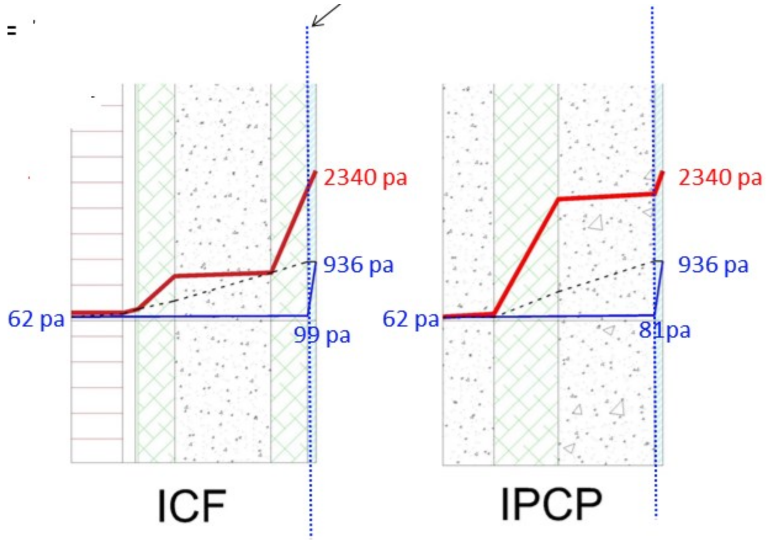
Here, the same calculation and adjustment and explanation as we done before would be applied for IPCP in table 13.

Table 13. Calculation of IPCP wall in terms of vapor transfer without and with vapor retarder



column1	column2	column8	column9	column10	column11	column12	column13	column14	column15	column16	column23	column24
IPCP Components	**Thickness**	**T**	**Saturation**	**vapor permeability**	**vapor permeance**	**Vapor Resistance**	**vapor pressure drop(dp1)**	**vapor pressure (Pv1)**	dp2	PV2	**dp with vapor retarder**	**Pv with vapor retarder**
	m	oc	Pa	ng/pa.s.m	ng/pa.s.m2	Pa.s.m2/ng	Pa	pa	pa	pa		pa
Outside		-20.0	103					62				
0												
Air Film		-19.7										
1			103					62		62		62
Exposed Concrete	0.08	-19.3		2.5	31.25	0.032000	245.754				5.47	
2			110					308		110		67
Insulation+membrane	0.1	17.3		4.66	46.60	0.021459	164.803				3.67	
3			1938					473				71
Interior Concrete	0.15	18.1		2.5	16.67	0.060000	460.788				10.25	
3.1			2064					933				81
Polyethelene sheet						5					854.55	
3.2												935.94
gypsum Borard	0.013	18.9		37.6	2892.31	0.000346	2.655				0.06	
4			2198					**936**				
Inside Air Film		20.0						936				936
5			2339									
Inside		20.0										
Total						0.113805 7680					R= 5.1138 w= 170.91	

Figure11. Based on table 12 and 14 these profile can be plotted



8.2 Appendix-B (ANP pairwise comparison and e-vectors)

Respect to PICP

Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**2.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.167**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**0.143**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**2.000**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	0.125	0.111	0.111	0.222	0.111
Space heating	8.000	1.000	0.889	0.889	1.778	0.889

	GWP	Energy	Weighted			Priorities
GWP	1.000	2.000	0.667	0.667	1.333	0.667
Energy	0.500	1.000	0.333	0.333	0.667	0.333

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities			
Moisture control	1.000	0.167	0.143	0.071	0.053	0.087		0.211	0.070			
R-value	6.000	1.000	0.500	0.429	0.316	0.304		1.049	0.350			
Thermal mass	7.000	2.000	1.000	0.500	0.632	0.609		1.740	0.580			
				1	1	1	0	3	1	0	0	0

	Aesthetic	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

Respect to PICP

Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**2.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.167**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**0.143**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**2.000**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	0.125	0.111	0.111	0.222	0.111
Space heating	8.000	1.000	0.889	0.889	1.778	0.889

	GWP	Energy	Weighted			Priorities
GWP	1.000	2.000	0.667	0.667	1.333	0.667
Energy	0.500	1.000	0.333	0.333	0.667	0.333

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities			
Moisture control	1.000	0.167	0.143	0.071	0.053	0.087		0.211	0.070			
R-value	6.000	1.000	0.500	0.429	0.316	0.304		1.049	0.350			
Thermal mass	7.000	2.000	1.000	0.500	0.632	0.609		1.740	0.580			
				1	1	1	0	3	1	0	0	0

	Aesthetic	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

Respect to WC

Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.333**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**2.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**3.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.500**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	0.125	0.111	0.111	0.222	0.111
Space heating	8.000	1.000	0.889	0.889	1.778	0.889

	GWP	Energy	Weighted			Priorities
GWP	1.000	0.333	0.250	0.250	0.500	0.250
Energy	3.000	1.000	0.750	0.750	1.500	0.750

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities			
Moisture control	1.000	2.000	3.000	0.545	0.571	0.500		1.617	0.539			
R-value	0.500	1.000	2.000	0.273	0.286	0.333		0.892	0.297			
Thermal mass	0.333	0.500	1.000	0.182	0.143	0.167		0.491	0.164			
				1	1	1	0	3	1	0	0	0

	Aesthetic	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

Respect to WW

Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.143**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.333**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**2.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**4.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.333**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	0.143	0.125	0.125	0.250	0.125
Space heating	7.000	1.000	0.875	0.875	1.750	0.875

	GWP	Energy	Weighted			Priorities
GWP	1.000	0.333	0.250	0.250	0.500	0.250
Energy	3.000	1.000	0.750	0.750	1.500	0.750

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities			
Moisture control	1.000	2.000	4.000	0.571	0.600	0.500		1.671	0.557			
R-value	0.500	1.000	3.000	0.286	0.300	0.375		0.961	0.320			
Thermal mass	0.250	0.333	1.000	0.143	0.100	0.125		0.368	0.123			
				1	1	1	0	3	1	0	0	0

	Aesthetic	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

Respect to Initial cost

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**0.250**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**3.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.500**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.333**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**3.000**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.333**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**3.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.250**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**5.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.143**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	0.250	3.000	0.500
PICp	4.000	1.000	0.333	3.000
WC	0.333	3.000	1.000	0.333
WW	2.000	0.333	3.000	1.000

Weighted					Priorities
0.136	0.055	0.409	0.103	0.703	0.176
0.545	0.218	0.045	0.621	1.430	0.357
0.045	0.655	0.136	0.069	0.905	0.226
0.273	0.073	0.409	0.207	0.961	0.240

	Initial cost	Space heating
Initial cost	1.000	0.125
Space heating	8.000	1.000

Weighted			Priorities
0.111	0.111	0.222	0.111
0.889	0.889	1.778	0.889

	GWP	Energy
GWP	1.000	3.000
Energy	0.333	1.000

Weighted			Priorities
0.750	0.750	1.500	0.750
0.250	0.250	0.500	0.250

	Moisture control	**R-value**	**Thermal mass**
Moisture control	1.000	0.250	5.000
R-value	4.000	1.000	7.000
Thermal mass	0.200	0.000	1.000

Weighted					Priorities
0.192	0.200	0.385		0.777	0.259
0.769	0.800	0.538		2.108	0.703
0.038	0.000	0.077		0.115	0.038
1	1	1	0	3	1

	Aesthetics	Health
Aesthetics	1.000	0.143
Health	7.000	1.000

Weighted			Priorities
0.125	0.125	0.250	0.125
0.875	0.875	1.750	0.875

Respect to space heating cost

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**2.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**5.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**4.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**4.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**3.000**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.500**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**8.000**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**3.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**4.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**5.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.143**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	2.000	5.000	4.000
PICp	0.500	1.000	4.000	3.000
WC	0.200	0.250	1.000	0.500
WW	0.250	0.333	2.000	1.000

Weighted					Priorities
0.513	0.558	0.417	0.471	1.958	0.490
0.256	0.279	0.333	0.353	1.222	0.305
0.103	0.070	0.083	0.059	0.314	0.079
0.128	0.093	0.167	0.118	0.506	0.126

	Initial cost	Space heating
Initial cost	1.000	8.000
Space heating	0.125	1.000

Weighted			Priorities
0.889	0.889	1.778	0.889
0.111	0.111	0.222	0.111

	GWP	Energy
GWP	1.000	3.000
Energy	0.333	1.000

Weighted			Priorities
0.750	0.750	1.500	0.750
0.250	0.250	0.500	0.250

	Moisture control	**R-value**	**Thermal mass**
Moisture control	1.000	4.000	5.000
R-value	0.250	1.000	7.000
Thermal mass	0.200	0.000	1.000

Weighted					Priorities
0.690	0.800	0.385		1.874	0.625
0.172	0.200	0.538		0.911	0.304
0.138	0.000	0.077		0.215	0.072
1	1	1	0	3	1

Respect to GWP

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**0.333**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**1.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.250**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**3.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.333**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.250**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.143**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.143**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.000**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	0.333	1.000	0.250
PICp	3.000	1.000	3.000	0.333
WC	1.000	0.333	1.000	0.250
WW	4.000	3.000	4.000	1.000

Weighted					Priorities
0.111	0.071	0.111	0.136	0.430	0.108
0.333	0.214	0.333	0.182	1.063	0.266
0.111	0.071	0.111	0.136	0.430	0.108
0.444	0.643	0.444	0.545	2.077	0.519

	Initial cost	Space heating
Initial cost	1.000	0.125
Space heating	8.000	1.000

Weighted			Priorities
0.111	0.111	0.222	0.111
0.889	0.889	1.778	0.889

	GWP	Energy
GWP	1.000	0.143
Energy	7.000	1.000

Weighted			Priorities
0.125	0.125	0.250	0.125
0.875	0.875	1.750	0.875

		R-value	**Thermal mass**
R-value		1.000	7.000
Thermal mass		0.143	1.000

Weighted					Priorities
	0.875	0.875		1.750	0.875
	0.125	0.125		0.250	0.125
0	1	1	0	2	1

	Aesthetics	Health
Aesthetics	1.000	0.000
Health	0.000	1.000

Weighted			Priorities
1.000	0.000	1.000	0.500
0.000	1.000	1.000	0.500

Respect to total energy demand

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**0.333**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**5.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**2.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**7.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**4.000**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.250**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.125**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.143**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.143**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	0.333	5.000	2.000
PICp	3.000	1.000	7.000	4.000
WC	0.200	0.143	1.000	0.250
WW	0.500	0.250	4.000	1.000

Weighted					
					Priorities
0.213	0.193	0.294	0.276	0.976	0.244
0.638	0.579	0.412	0.552	2.181	0.545
0.043	0.083	0.059	0.034	0.219	0.055
0.106	0.145	0.235	0.138	0.624	0.156

	Initial cost	Space heating
Initial cost	1.000	0.125
Space heating	8.000	1.000

Weighted			Priorities
0.111	0.111	0.222	0.111
0.889	0.889	1.778	0.889

	GWP	Energy
GWP	1.000	0.143
Energy	7.000	1.000

Weighted			Priorities
0.125	0.125	0.250	0.125
0.875	0.875	1.750	0.875

		R-value	**Thermal mass**
R-value		1.000	7.000
Thermal mass		0.143	1.000

Weighted					Priorities
	0.875	0.875		1.750	0.875
	0.125	0.125		0.250	0.125
0	1	1	0	2	1

Respect to Moisture control

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**3.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.250**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.250**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.143**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.143**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**1.000**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**6.000**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**3.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**4.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.500**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.167**

	ICFs	**PICp**	**WC**	**WW**	Weighted					Priorities
ICFs	1.000	3.000	0.250	0.250	0.107	0.167	0.104	0.104	0.483	0.121
PICp	0.333	1.000	0.143	0.143	0.036	0.056	0.060	0.060	0.211	0.053
WC	4.000	7.000	1.000	1.000	0.429	0.389	0.418	0.418	1.653	0.413
WW	4.000	7.000	1.000	1.000	0.429	0.389	0.418	0.418	1.653	0.413

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	6.000	0.857	0.857	1.714	0.857
Space heating	0.167	1.000	0.143	0.143	0.286	0.143

	GWP	Energy	Weighted			Priorities
GWP	1.000	0.000	#DIV/0!	0.000	#DIV/0!	#DIV/0!
Energy	#DIV/0!	1.000	#DIV/0!	1.000	#DIV/0!	#DIV/0!

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities
Moisture control	1.000	3.000	4.000	0.632	0.750	0.571		1.953	0.651
R-value	0.333	1.000	2.000	0.211	0.250	0.286		0.746	0.249
Thermal mass	0.250	0.000	1.000	0.158	0.000	0.143		0.301	0.100
				1	1	1	0	3	1

	Aesthetics	Health	Weighted			Priorities
Aesthetics	1.000	0.167	0.143	0.143	0.286	0.143
Health	6.000	1.000	0.857	0.857	1.714	0.857

Respect to R-value

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**2.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**4.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**4.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**2.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**2.000**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**1.000**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.143**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.143**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.250**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**4.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.143**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	ICFs	**PICp**	**WC**	**WW**	Weighted					Priorities
ICFs	1.000	2.000	4.000	4.000	0.500	0.500	0.500	0.500	2.000	0.500
PICp	0.500	1.000	2.000	2.000	0.250	0.250	0.250	0.250	1.000	0.250
WC	0.250	0.500	1.000	1.000	0.125	0.125	0.125	0.125	0.500	0.125
WW	0.250	0.500	1.000	1.000	0.125	0.125	0.125	0.125	0.500	0.125

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	0.143	0.125	0.125	0.250	0.125
Space heating	7.000	1.000	0.875	0.875	1.750	0.875

	GWP	Energy	Weighted			Priorities
GWP	1.000	0.143	0.125	0.125	0.250	0.125
Energy	7.000	1.000	0.875	0.875	1.750	0.875

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities
Moisture control	1.000	0.250	4.000	0.190	0.200	0.333		0.724	0.241
R-value	4.000	1.000	7.000	0.762	0.800	0.583		2.145	0.715
Thermal mass	0.250	0.000	1.000	0.048	0.000	0.083		0.131	0.044
				1	1	1	0	3	1

	Aesthetics	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

Respect to thermal mass

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**1.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**5.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**7.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**5.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**7.000**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**3.000**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**0.143**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.500**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.250**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**4.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.167**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.000**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	1.000	5.000	7.000
PICp	1.000	1.000	5.000	7.000
WC	0.200	0.200	1.000	3.000
WW	0.143	0.143	0.333	1.000

Weighted						Priorities
0.427	0.427	0.441	0.389		1.684	0.421
0.427	0.427	0.441	0.389		1.684	0.421
0.085	0.085	0.088	0.167		0.426	0.106
0.061	0.061	0.029	0.056		0.207	0.052

	Initial cost	Space heating
Initial cost	1.000	0.143
Space heating	7.000	1.000

Weighted				Priorities
0.125	0.125		0.250	0.125
0.875	0.875		1.750	0.875

	GWP	Energy
GWP	1.000	0.500
Energy	2.000	1.000

Weighted				Priorities
0.333	0.333		0.667	0.333
0.667	0.667		1.333	0.667

	Moisture control	**R-value**	**Thermal mass**
Moisture control	1.000	0.250	4.000
R-value	4.000	1.000	6.000
Thermal mass	0.250	0.000	1.000

Weighted					Priorities
0.190	0.200	0.364		0.754	0.251
0.762	0.800	0.545		2.107	0.702
0.048	0.000	0.091		0.139	0.046
1	1	1	0	3	1

	Aesthetics	Health
Aesthetics	1.000	0.000
Health	#DIV/0!	1.000

Weighted				Priorities
#DIV/0!	0.000		#DIV/0!	#DIV/0!
#DIV/0!	1.000		#DIV/0!	#DIV/0!

Respect to aesthetics

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**4.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.200**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.200**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.143**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.125**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.500**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**9.000**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**7.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**6.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.500**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**7.000**

	ICFs	**PICp**	**WC**	**WW**
ICFs	1.000	4.000	0.200	0.200
PICp	0.250	1.000	0.143	0.125
WC	5.000	7.000	1.000	0.500
WW	5.000	8.000	2.000	1.000

Weighted					Priorities
0.089	0.200	0.060	0.110	0.458	0.115
0.022	0.050	0.043	0.068	0.183	0.046
0.444	0.350	0.299	0.274	1.368	0.342
0.444	0.400	0.598	0.548	1.991	0.498

	Initial cost	Space heating
Initial cost	1.000	9.000
Space heating	0.111	1.000

Weighted			Priorities
0.900	0.900	1.800	0.900
0.100	0.100	0.200	0.100

	GWP	Energy
GWP	1.000	0.000
Energy	#DIV/0!	1.000

Weighted			Priorities
#DIV/0!	0.000	#DIV/0!	#DIV/0!
#DIV/0!	1.000	#DIV/0!	#DIV/0!

	Moisture control	**R-value**	**Thermal mass**
Moisture control	1.000	7.000	6.000
R-value	0.143	1.000	2.000
Thermal mass	0.167	0.000	1.000

Weighted					Priorities
0.764	0.875	0.667		2.305	0.768
0.109	0.125	0.222		0.456	0.152
0.127	0.000	0.111		0.238	0.079
1	1	1	0	3	1

	Aesthetics	Health
Aesthetics	1.000	7.000
Health	0.143	1.000

Weighted			Priorities
0.875	0.875	1.750	0.875
0.125	0.125	0.250	0.125

Respect to health aspects

ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**PICP**	**4.000**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.500**
ICF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**2.000**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WC**	**0.333**
PICP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**0.333**
WC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**WW**	**1.000**
Initial cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Space heating**	**8.000**
GWP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Energy**	**0.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**6.000**
Moisture control	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Thermal mass**	**6.000**
Thermal mass	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**R-value**	**0.500**
Aesthetics	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Health aspects**	**0.143**

	ICFs	**PICp**	**WC**	**WW**	Weighted					Priorities
ICFs	1.000	4.000	0.500	2.000	0.267	0.364	0.176	0.462	1.268	0.317
PICp	0.250	1.000	0.333	0.333	0.067	0.091	0.118	0.077	0.352	0.088
WC	2.000	3.000	1.000	1.000	0.533	0.273	0.353	0.231	1.390	0.347
WW	0.500	3.000	1.000	1.000	0.133	0.273	0.353	0.231	0.990	0.247

	Initial cost	Space heating	Weighted			Priorities
Initial cost	1.000	8.000	0.889	0.889	1.778	0.889
Space heating	0.125	1.000	0.111	0.111	0.222	0.111

	GWP	Energy	Weighted			Priorities
GWP	1.000	0.000	#DIV/0!	0.000	#DIV/0!	#DIV/0!
Energy	#DIV/0!	1.000	#DIV/0!	1.000	#DIV/0!	#DIV/0!

	Moisture control	**R-value**	**Thermal mass**	Weighted					Priorities
Moisture control	1.000	6.000	6.000	0.750	0.857	0.667		2.274	0.758
R-value	0.167	1.000	2.000	0.125	0.143	0.222		0.490	0.163
Thermal mass	0.167	0.000	1.000	0.125	0.000	0.111		0.236	0.079
				1	1	1	0	3	1

	Aesthetics	Health	Weighted			Priorities
Aesthetics	1.000	0.143	0.125	0.125	0.250	0.125
Health	7.000	1.000	0.875	0.875	1.750	0.875

8.3 Appendix-C (Questionnaire)

Dear Participant,

We are conducting an academic research project on two types of exterior walls including "wood-frame" and "insulated concrete wall" for application in residential buildings in Canada. In this regards, experts' opinion are needed on evaluating these alternative walls. The purpose of this study is to identify and evaluate preferred exterior wall alternatives which could influence on space heating energy, cost, and environmental. In the following pages we would like to obtain your opinion as an expert through a survey questionnaire. The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated.

We sincerely hope you can assist.

Ali.

Ali Jafarpour MASc student at Concordia University

1455 Boulevard de Maisonneuve O, Office# EV.9.412 Montréal, QC H3G 1M8

a_jafarp@encs.concordia.ca or ali.jafarpour@gmail.com

Cellphone: 438 990 1077

Information for participant

Key terms: Four main key terms are chosen in this evaluation that these are:

1. Well-being: referring to occupants health and comfort as well as aesthetics
2. Hygrothemal performance: The capability to control heat and moisture movements
3. Cost: Including initial cost (construction cost), space heating cost over use phase, and demolition cost
4. Environmental Impacts: Impacts on global warming potential, total embodied and primary energy over entire life span of a building.

Exterior wall alternatives: Three types of exterior walls are identified on four types of building as following:

1. ICFs house: A single family house where ICFs (insulated concrete forms) walls act as a main structure as well as exterior walls
2. PICP house: Pre-cast insulated concrete panel walls are consider as a main structure and exterior walls.
3. Wood frame with concrete stricter (WC) house: A house that its exterior walls are wood-frame and main structure is made of reinforcement concrete.
4. Wood frame with wood structure (WW) house: A single family house where both exterior walls and main structure are constructed with wood materials.

In the following sheets, we would like to elicit your opinion in order to select amongst the alternatives. The pair wise comparison scale is used to express the importance of one element over another.

Example:

Given two Options, you can judge their relative importance as shown below example: if you think the option 'Cost' is strongly more important than the option 'Well-being', then you mark strongly with (*) on the table. Also if you think the option 'Environmental impact is extremely more important than 'Cost', then you mark extremely with (*).

	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	Very strong	Very very strong	Extremely	
Cost					*													**Well-being**
Environmental impacts	*																	**Cost**

With respect to **choose an exterior wall on main criteria**																			
	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	strong	Very strong	Very very strong	Extremely	
Well-being																			**Hygrotherml performance**
Well-being																			**Cost**
Well-being																			**Environmental Impacts**
Hygrothermal performance																			**Cost**
Hygrothermal performance																			**Environmental Impacts**
Environmental impacts																			**Cost**

With respect to Well-being																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**Very strong**	**Very very strong**	**Extremely**	
Health aspects																		**Aesthetics**

With respect to Environmental impacts																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**Very strong**	**Very very strong**	**Extremely**	
GWP																		**Total energy**

With respect to **choose an exterior wall from its health aspects**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**Very strong**	**Very very strong**	**Extremely**	
ICF																		**PICP**
ICF																		**Wood-frame**
Wood-frame																		**PICP**

With respect to **choose an exterior wall from its aesthetics**

	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**Very strong**	**Very very strong**	**Extremely**	
ICF																		**PICP**
ICF																		**Wood-frame**
Wood-frame																		**PICP**

`Investigator: Ali Jafarpour, MASc student

Supervisor: Prof. Fuzhan Nasiri

CONSENT FORM

Dear Participant,

This is an academic research project regarding exterior walls in residential buildings in Canada which is conducted by Ali Jafarpour under the supervision of Prof. Fuzhan Nasiri. In this study you are being asked to participate in this research.

In case of any question or need to clarification you should ask Mr. Ali Jafarpour to explain it. You can email your questions or call to investigator which his number is provided at the end of this form.

If you decide to participate in this research, please complete the survey and return it directly to the researcher

By completing and returning the attached survey, you are consenting to participate in this research.

Information for Participants

Participants

Experts are identified as key participants of this study. Experts include those identified as having an extensive knowledge of building envelope, passive building, sustainability in building sector, energy efficiency in building, and other relevant area in buildings. Experts are expected to include university academics, professional engineers, planners, and etc.

Participants' Right to Decline

Your participation is voluntary and you can withdraw from the survey after having agreed to participate. You are free to refuse to answer any question that is being asked in the questionnaire.

Confidentiality

The information provided by participants will not be disclosed. Participant's name, address and other personal data are not asked, however, if provided, they will be removed from the questionnaire and not known to others. The answers he or she gives will be only used for research purposes and for writing a report. Care will be taken to report information so as to minimize the readers' ability to identify the role and hence identity of the source of information.

Use of Information: The information and findings obtained will be used for completing the requirements for the degree of MASc thesis. In addition, they may be used in seminars, conference presentations and research publications.

Availability of Results

A summary of the results is expected to be available by March 2017. Participants wanting a copy upon request forward their request directly to Ali Jafarpour at Concordia University, by email to: a_jafarp@encs.concordia.ca, or by phone: 4389901077.

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Contact Numbers
For answers to questions about the research or to voice concern or complaint about the research, or to report a study-related problem:

Ali Jafarpour
MASc student at Concordia University
438-990-1077
a_jafarp@encs.concordia.ca