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INTEGRATED BUILDING DESIGN AND ENERGY SIMULATION

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Abstract: Energy consumption in buildings constitute a significant portion of the total energy demand in Canada (about 40%). While the design and construction of energy efficient buildings is gaining momentum, it is important to have an integrated process for the design. The present article focuses on the integrated design process at the conceptual phase to account for energy efficiency and adoption of renewable energy in buildings. The research is divided into three phases. Phase one includes the optimization of the design of a single-family home in Montreal based on the following criteria; space, aesthetics, energy performance and cost. Each of the above criteria was evaluated over 22 designs and the importance of each category weighted according to public opinion. As a result, cost was considered as the most important category (weighting of 30%), followed by space (28%), energy performance (25%) and aesthetics (17%). The top three designs are further evaluated. Phase two, includes a detailed analysis of the building envelope, following the insulation requirements of the Quebec Construction Code. An energy analysis was conducted and the top performing building was selected for further analysis. Characteristics of the top performing building include, simple building geometry, a brick façade, windows located on the North and South façade, and a hip roof over the living area with a flat roof over the garage. The energy analysis results are carried over to phase three, where the possibility of renewable and sustainable energy saving techniques are explored to reduce external energy requirements.

1 INTRODUCTION

It is estimated that the energy consumption in buildings is quite significant as compared to the total energy demand in Canada (about 40%). Design and construction of energy efficient buildings is gaining momentum, and it is important to have an integrated process for the design. Energy performance is of top concern in today's construction market, and it is important to recognize how it can be incorporated into the design and construction of a project without compromising on other important aspects, such as aesthetics, space and cost. A balance between all elements is necessary to achieve a home which satisfies the owners requirements. The following report takes into consideration homeowners' priorities and establishes the possibilities of how to reduce energy consumption and lower the dependency on non-renewable energy sources.

Integrated design process for buildings starts right at the conceptual phase. The goal of the present work is to develop an optimal design process for single-family homes considering several factor including cost and sustainability, and additionally exploring current-market materials satisfying envelope and energy regulations set out in the Quebec Construction Code established by the National Research Council of Canada (2005). Furthermore, to determine the effects of implementing renewable energy techniques to reduce owners operating costs and harmful environmental effects, though gathered information from the National Renewable Energy Laboratory and related work by Eslami-Nejad et al. (2016).

2 PHASE 1

2.1 Overview of Phase 1

Phase 1 commenced with the conceptual design of 22 single family homes which are modeled in a Building Information Modelling (BIM) software, Autodesk Revit 2017. All the designs satisfy the same criteria; a 2-storey, 4-bedroom, single family home with an unfinished basement located in Montreal, Québec. Each design was evaluated based on space, aesthetics, energy performance and cost. Each criterion has been subdivided below and the process of how they have been evaluated explained.

2.2 Space

During the design of each of the 22 homes, careful consideration was given to ensure realistic room sizes for the variety of spaces within the home. Space was evaluated based on the square footage of each of the rooms within the house. The larger the room, the more points it received and vise-versa. As the overall building dimensions of all 22 designs fall within the livable square footage of between 2,250 sq. ft. to 2,750 sq. ft., the cumulative score for each design are relatively similar, as when a design received high points in one area, it received lower in another. All designs received a total score of between 46-59% in the space category. The higher scoring designs had the largest family rooms, dining rooms and master bedrooms.

2.3 Aesthetics

As aesthetics are subjective and opinions vary from person to person, the Birkhoff's Aesthetic Measure was used to assign a score to each of the designs (Megahed and Gabr 2010). The total score is based on the aesthetics measure which is a ratio of order to complexity. Order is evaluated based on symmetry, repetition, equilibrium, disposition and colour harmony, and includes a point deduction for randomness and uncomfortable looking elements. Complexity evaluates form complexity, ornaments, silhouette differentiation and colour contrast. The ratio between the two, order/complexity, gave a total score for each of the 22 designs.

According to Magahed and Gabr (2010), a design receiving a score between 0.125-1 has poor architectural aesthetics, between 2-4 is fairly aesthetic and from 4-10, highly aesthetic (Megahed and Gabr 2010). The designs receiving the highest scores displayed simple external geometry with local symmetry, had a large amount of reoccurring identical objects on the building elevations with uniform colours, had perfect equilibrium and conventional building grids. They also had plain masses and plain facades with no ornate detail and the least number of turns on the façade.

It is important to keep in mind that this measure for evaluating aesthetics, still involves some qualitative parameters, such as assigning the values within each category. However, the need of evaluating the building as a whole is eliminated, reducing the subjective nature and the effect of personal opinion. It is also important to note that the Birkhoff's Aesthetic Measure does not consider any historical implications and it also does not take into account the buildings function. In the case of evaluating the 22 house designs, neither of these limitations need to be considered as they are of the same age and share the same function.

2.4 Energy Performance

Each of the 22 single-family home designs were evaluated based on energy performance using Autodesk Revit's 2017 built-in energy analysis. For the initial evaluation, the homes were evaluated using Autodesk Revit's 2017 default conceptual building envelope compositions. The energy settings for each of the designs were consistently set to be uniform across all designs for direct comparison. The results were evaluated based on two criteria, the annual energy cost per area and the renewable energy potential.

The area used in the calculation for determining the energy usage per area, is the total floor area as analyzed by Autodesk Revit 2017, which includes the livable floor area, as well as the garage and basement slab. The analytical surfaces analyzed include the above and below ground exterior wall, the interior walls and floors, the basement slab and the glazing modeled within the project. As a result, the design achieving the highest score in the energy performance category had the following characteristics; the building geometry is very simple, with the main living area as a rectangle. The garage is attached to the house but does not include a livable area above. The main house has a simple hip roof design, with a flat roof over the garage. The window to wall ratio calculated as 0.07, with the windows equally distributed on all façades of the building. Among the other top scoring buildings in this category, it can be observed that the building geometry is simple, excluding any large protrusions, the roof designs are simple, for the most part being of hip design, and the window to wall ratios range between 0.06 and 0.10. An energy efficient building should have a simple geometry and should have the largest volume for the smallest surface/envelope area (Low Energy Home: building an energy efficient passive house n.d.). Ideally, a sphere is the optimal shape, having the smallest area to volume ratio. However as this is not an ideal shape for the construction of a single-family home, a simple square or rectangular building foot print is the next best option.

2.5 Cost

The final criterion considered in phase 1 is the initial construction cost of the building. To evaluate this criterion, the 2018 Canadian Cost Guide published by the Altus Group (2018), was consulted. According to this guide, wood-frame residential construction of a single-family home with an unfinished basement in Montreal ranges from $95-160/ft^2. The guide explains that the correct area to be used is the area of all livable space, not including the basement or garage area, measured to the exterior of the exterior walls with no deductions made for staircase openings. The average of this construction cost was used and evaluated at $127.50/ft^2.

As the cost is directly related to square footage, the larger houses received lower scores when compared to the smaller sized homes. A separate, small point deduction was subtracted to designs that had extras, such as balconies, to incorporate the additional expenses.

2.6 Weighting Criteria and Selection of Top 3 Designs

As to not consider space, aesthetics, energy performance and cost as equally important when designing a new home, a survey was conducted to ask the public their opinion. The following question was asked, “When designing your home, what do you consider the most important between the following options?”. All possible combinations were explored, cost/aesthetics, space/energy performance, cost/energy performance, aesthetics/space, cost/space and lastly, aesthetics/energy performance. The results were analyzed based on the number of times a response was selected divided by the total number of possible times a response could have been selected.

Out of the three questions involving cost as an option, the majority of people selected cost as more important in every question. More than double when compared to aesthetics, 25% more than space and only 9% when compared to energy performance. Out of the possible 63 times cost could have been selected, it was selected 38 times (60.3%). In terms of importance, cost was followed by space. Out of the three questions involving space, 2/3 times space resulted as the winning option, above energy performance (by 38%), and above aesthetics (by 38%). The only category it did not receive the majority of votes was when it was compared to cost. Out of the possible 63 times it could have been selected, it was selected 35 times (55.6%). Energy performance ranked next, winning 1/3 possible questions. It received 38% more votes when compared to aesthetics but fell below when compared to both cost and space. Out of the possible 63 times it could be selected, it was chosen 31 times (49.2%). Lastly, aesthetics did not win any question as the majority vote, being selected 22 times out of the possible 63 (34.9%).

Summarizing the results, cost ranked as the most important attribute, followed by space, energy performance and lastly aesthetics and were assigned a weighting factor (Cost – 30, Space – 28, Energy

Performance – 25, Aesthetics – 17). This weighting factor was then multiplied to the points assigned to each design and resulted in the top 3 designs averaging a score of between 68-70%.

3 PHASE 2

3.1 Overview of Phase 2

Phase 2 of the project involved implementing current-market building envelope materials to have a realistic envelope composition. The top three designs carried forward from phase 1, were each further analyzed based on their energy consumption with the new adjustments of envelope materials and the top performing design was selected to move forward into phase 3 of the project.

3.2 Current Market Materials

Meeting with a local Montreal architect, it was determined that one of the most popular types of insulation used in today's residential construction market is a spray-polyurethane insulation. One of the products discussed was Heatlok Soya spray polyurethane insulation manufactured by Demilec (Demilec 2018). This spray foam insulation is a medium density, type 2 insulation. It meets all requirements set forth by the National Building Code of Canada and the Natural Research Council of Canada to double as an air-barrier system. It is manufactured from recycled plastic material, soya oil, and has zero ozone depleting substances, meeting the requirements of the Montreal protocol to protect the ozone layer. It is also Greenguard Gold certified, exceeding the requirements set forth for volatile organic compounds (Demilec 2018). As this insulation is a closed-cell, it also acts as a vapour barrier. For the above reasons, this product was chosen as the main insulating material applied throughout the houses.

Set out in the insulating requirements required by the Quebec Construction Code, amended for the province from the National Building Code of Canada 2010, and adopted by the Régie du Bâtiment Québec, the envelope of all new buildings must have a continuous insulation layer of at least R-4, to break thermal bridging (Isolation Majeau et frère 2018). For this purpose, it was decided to implement an extruded polystyrene rigid insulation.

3.3 Required Insulating Values and Envelope Composition

Following the presently mandatory requirements established in Part 11 of the Quebec Construction Code, the building envelope composition was designed in Autodesk Revit 2017 to incorporate the correct thermal properties for the building envelope construction, consisting of an insulating value of R-41 for the roof, R-24.5 for the exterior walls, R-17 for the foundation wall and finally R-5 for the basement slab, with a thermal bridge covering of a minimum R-4 for all of the assembly (National Research Council of Canada 2005). Figure 1 below shows a graphical representation of the roof composition (left) and wall assembly (right) modeled in Revit.

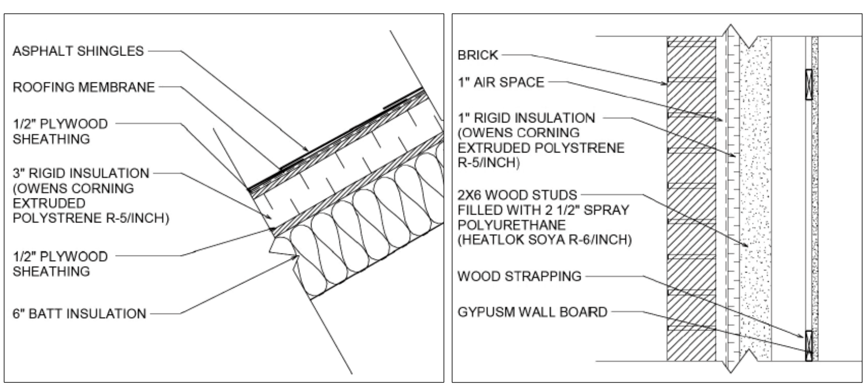

Figure 1: Roof and wall assembly

The minimum insulation requirements outlined in the QCC, are considered total R-values, this takes into consideration the R-value through the entire composition, not solely the insulation. It is important to note however that when Revit uses the detailed building envelope composition, it does not consider thermal bridging, therefor the estimation of heat loss may be less than the actual value.

3.4 Energy Analysis

An energy analysis was then performed on the top three designs with the modified building envelopes. The Revit designs were set up using spaces, as with spaces it is possible to directly set the building type parameters for single family home, define if the space is occupiable, as well as define if the space should be heated or cooled. The results allowed for a direct comparison of annual cost /ft^2 of each design as well as the renewable energy potential. For the top three designs, the annual cost/area was almost identical, varying by only \$0.01/ft^2. As this was the case, the energy use intensity as well as the renewable energy potential were the main distinguishing factors. The top design for this category was then selected.

4 PHASE 3

4.1 Overview

Phase three of the project commenced by reviewing the building design, to optimize energy performance. Autodesk Insight 360 was used to determine which building parameters had the greatest potential for reducing energy demand. Additionally, it was verified that the results given through the Revit energy analysis are realistic and compare to similar buildings in operation today. Lastly, renewable energy techniques were explored to determine their impact if implemented into the current design.

4.2 Envelope and Load Modification

According to Transition Énergétique Québec, the highest heat loss is observed through above ground walls (17%), followed by the basement walls and foundations (15%) and lastly through the roof (11%) (Transition énergétique Québec n.d.). The results from Insight 360 implied that modifying the thermal resistance of the exterior walls would have a positive impact on the yearly energy consumption. Modifying the composition to a thermal resistance of R-31, adding an additional resistance of 6.5 h.ft^2°F/BTU, positively impacted the annual energy cost per area by reducing it to \$0.81/ft^2. Other suggested modifications included increasing infiltration, reducing the plug load and reducing the lighting load. Internal loads were reduced to approximately half of the initial value and were modeled at approximately 0.5 W/ft^2. Applying this modification, the annual energy cost per unit area was reduced to \$0.64/ft^2.

4.3 Comparison of Results to Similar Buildings

To verify the results of the energy simulation, a comparison was done between the model and an existing building, as well as compared with results from Statistics Canada (Statistics Canada 2011).

The existing home used for the comparison, as well as the homes surveyed by Statistics Canada, use forced air furnaces as the main system type, with heat pumps not being included in the survey results at all. The current Revit model is modeled using one of Revit's pre-defined domestic HVAC systems, Residential 17, with a heat pump as the system type. For this reason, to compare models, the energy analysis was re-run using Revit's pre-defined HVAC system Residential 14, which uses a gas-powered forced air furnace.

The results of the annual energy consumption, calculated by Revit for both HVAC system types, was compared to the existing home of similar size in the same location, and to an average found in Table 4-3: "Average household energy use, by household and dwelling characteristics 2011 – Dwelling Type", of Statistics Canada: *Households and the Environment Energy Use 2011* (Statistics Canada 2011). A summary of comparisons is outlined in table 1.

Table 1: Comparison between Revit models, existing home and statistics

Model	Annual Energy Consumption (kWh)	Heated Floor Area (ft^2)	Annual Energy Consumption / Area (kWh/ft^2)
Revit - heat pump	39,379	2172	18.13
Existing house - gas furnace	44,563	1940	22.97
Statistics Canada	57,795	2172	26.61
Revit – gas furnace	56,005	2172	25.78

Analyzing the results, it can be observed that the Revit model with the gas furnace, is directly comparable to the Statistics Canada results, falling within the same range of approximately 60,000 kWh. When comparing the results of the Revit models to the existing house, the annual energy consumption of the existing home falls between the two models, however closer to the model with the gas furnace as the systems are more closely correlated. The slight reduction in the annual consumption in the existing house can be attributed to the fact that the home is equipped with a smart thermostat, regulating energy use and reducing the heating and cooling demands according to the occupant's schedule.

4.4 Investigating Solar Energy Potential

The first step in analyzing the potential for solar energy implementation was investigating the available space for the installation of the photo-voltaic panels. The modeled home has a hip roof over the main living area of the house, as well as a flat roof over the garage. As solar power has the largest potential for power generation facing south, the area of the hip roof facing south was measured, along with the flat roof over the garage. The total measured roof area available for the installation of the panels equals 1055 ft^2. The PV energy production was calculated using Revit's Solar Analysis as well as PVWatts, a calculator created by the National Renewable Energy Laboratory (National Renewable Energy Laboratory n.d.). The results given by Revit, estimate a possible 18,474 kWh/year that can be generated by the PV panels. Using PVWatts, the estimated annual generation was 17,839 kWh/year. According to Québec Solar, the cost of installing a 10kW system, of approximately 40 panels, is $26,000, relating this to the system designed below, the estimated cost for implementing such a system, of 56 panels, would be approximately $36,400 (Quebec Solar 2018).

As explained in the PVWatts documentation, the DC system size was calculated based on the module name plate size, which was estimated at 250 Watts, multiplied by the number of panels, 56, divided by 1000 to convert Watts to Kilowatts, totaling 14 kW. The name plate size as well as the panel dimensions were taken from Québec Solar (Quebec Solar 2018).

The standard module type implies crystalline silicon cell material, with an approximate nominal efficiency of 15%, with a glass module cover. It also implies a 0.47% reduction for every degree Celsius temperature rise. The fixed roof mount array type assumes limited air flow between the roof surface and the back of the panel. The system losses are calculated based on default values including, a 2% loss for panel soiling, 3% for shading, 0% for snow, 2% for mismatch, 2% for wiring, 0.5% for connections, 1.5% light-induced degradation, 1% nameplate rating, 0% for age and 3% for availability. The tilt of 30% was selected based on the slope of the modeled roof as well as the recommended value for the area according to Québec Solar (Quebec Solar 2018). The azimuth of 180 degrees represents direct south facing orientation.

As the modeled home uses electricity for all energy needs, excluding the domestic hot water heating, its total annual electrical consumption is 35,453 kWh. Assuming that the PVWatts calculation is correct, an annual generation of 17,839 kWh/year results in the generation of approximately half of the electrical energy consumption of the modeled home. However, this calculation is over estimating the possible generation as it does not account for the shading that would currently happen due to the panel arrangement, as well as the losses attributed to snow coving in the winter.

To implement the 56 panels that have been estimated in the above calculation, 36 of the panels must be installed on the flat roof over the garage. This installation would be done in a sawtooth pattern, resulting in the panels being close to one another and casting shadows on the ones behind. This layout greatly reduces the potential energy generation as the panels surface exposure has been reduced. A comparison of the two panel layouts can be seen in figure 2.

Calculating the correct spacing required for this arrangement, taking into consideration the worst possible scenario (considering the suns position on the winter solstice), the minimum row spacing results in 8'-5" apart (Affordable Solar 2016) (National Oceanic & Atmospheric Administration 2018). This requirement reduced the total number of panels that can be installed to 38 panels, having 18 installed on the flat roof. Inputting this data into PVWatts, now having a DC system size of 9.5 kW, the potential energy generation falls to 12,105 kWh/year, a 5,734 kWh/year reduction.

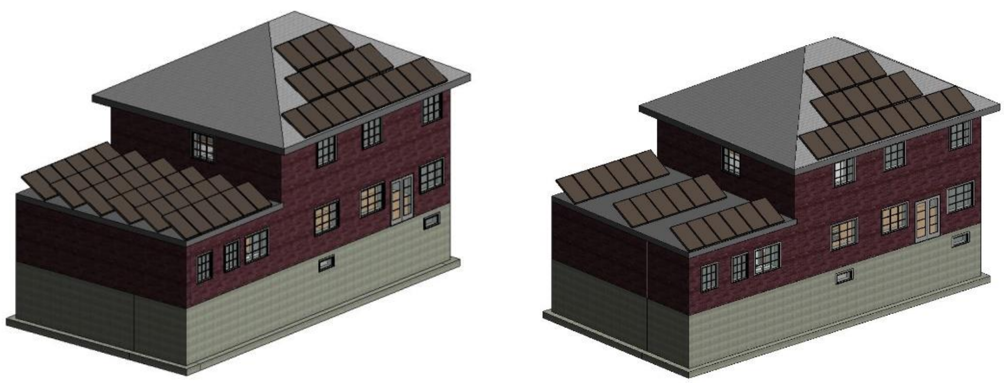

Figure 2: Original panel configuration compared to modified configuration

Further analyzing the potential energy generation, the system losses due to snow covering was also investigated. Research published by the National Renewable Energy Laboratory, monitored trends in snow losses across the U.S. (Ryberg and Freeman 2017). As the results are for US cities, the average snow loss found for Burlington, VT was used for Montreal. The results imply an estimate of 8%. Applying this to the PVWatts calculator, the potential energy generation from the PV panels is now estimated to be 10,901 kWh/year, approximately 31% of the overall consumption.

Comparing this result to data collected by Natural Resources Canada (NRCAN), the average solar system, of 5 kW produces 5,766 kWh/year in Montreal (Solar Panel Power Canada 2018). As the system implemented above is estimated to be 9.5 kW, approximately 1.9 times larger, correlating this to the collected data the system should produce roughly 10,955 kWh/year, almost exactly what was calculated.

4.5 Investigating Geothermal Energy Potential

Another renewable energy source that was investigated for use within the designed home is geothermal energy, using the land around the home to provide heating and cooling to the building. The impacts of geothermal implementation were investigated through literature review.

In the *Technical Assessment of Ground-Source, Air-Source, and Hybrid Heat Pumps for Single-Family Buildings in Cold Climates*, a comparison is made between operating a direct-expansion ground-source heat pump (GSHP) compared to an air-source heat pump (ASHP) (Eslami-Nejad, et al. 2016). The details of the home used for the modeling of the heat pump configurations is very similar to the modeled home in Revit, both being a single-family home located in Montreal with an approximate floor area of 2,200 ft^2.

The modeled system in TRNSYS, described by Eslami-Nejad et al (2016), includes the heat pump as well as a back up electric heater. It was found that over a 10-year period, the ASHP could generate between 48-82% of the required heat, while the GSHP generated between 46-98%, depending on the capacity as well as the number of boreholes. It was determined that for both air and ground source heat pumps, the higher capacity heat-pumps generated more of the heating demand. The number of boreholes also play a large role, as the same capacity heat-pump with more boreholes generated 12% more energy (Eslami-Nejad, et al. 2016). The energy consumption of the systems was also taken into consideration. When comparing the high capacity heat pumps, it was found that over a 10-year period, the GSHP consumed approximately 30 MWh less than the ASHP (Eslami-Nejad, et al. 2016). Concluding that high capacity heat-pumps, with a nominal heat-capacity of 9.3 kW, with the proper number of boreholes, can generate almost all the heating requirements, while consuming less energy, when compared to ASHP (Eslami-Nejad, et al. 2016).

Although there is a higher initial investment, there are long term savings for heating and cooling a home using geothermal energy.

4.6 Cost Comparison

Comparing the annual operating cost of each of the HVAC techniques explored above, it is recognizable that with the implementation of renewable energy sources, there is a large potential to not only reduce non-renewable energy, but also reduce operating costs.

Using the results from the Revit energy analysis, the annual energy consumptions were used to estimate the annual energy costs. To accurately estimate the annual costs across all HVAC designs, the current costs of electricity and gas were determined consulting Hydro-Quebec and Énergir energy bills. The current price for electricity is \$0.0591/kWh plus a base fee of \$0.4064/day (Hydro-Québec 2018). The price for natural gas, including supply, transportation, load-balancing, inventory-related adjustments, distribution and cap-and-trade emission allowance system, consulting 2017 energy bills and the Énergir website, total \$0.53/m^3 plus a base fee of \$0.5412/day (Énergir 2018). Using this information, it was estimated that the modeled home with the gas furnace will cost \$3259.42/year in energy costs and the one with the air-source heat pump, \$2627.13/year. To estimate the potential annual savings incurred by installing a 9.5kW PV-system on the south facing roofs of the home, the potential generation was deducted from the current energy bill of the ASHP model and resulted in annual savings of \$644.25. The geothermal cost savings were calculated using an online calculator published by BOSCH (BOSCH 2018). This calculator estimates the potential energy savings by inputting the current details of the home, such as age, heated area and energy efficient measures taken. The estimate was that the installation of a geothermal system in the current home would result in an annual cost of \$927.00 for heating, cooling and hot water. Adding this to the energy cost for lighting and miscellaneous equipment, the total was calculated to be \$1569.54/year. Finally, combining the PV-system with the geothermal system, it was estimated that the total annual energy costs would reduce to \$925.29. The electricity generated by the PV panels can be used to supply the power demand of the pumps and other electrical loads incurred. A summary of annual energy costs according to the corresponding systems can be seen in Figure 3.

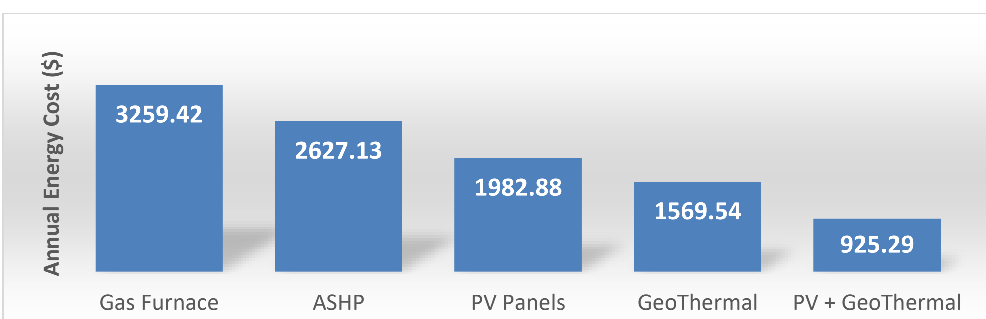

Figure 3: Annual cost comparison of HVAC systems

5 CONCLUSION

This research project has explored the optimal design of a single-family home in Montreal, considering energy performance, cost, space and aesthetics. The findings from phase 1, conclude that of the above criteria, cost is considered most important, having a weighting factor of 30%, followed by space at 28%, energy performance at 25% and aesthetics at 17%. It was found that the designs ranking the highest in the space category, had the largest family rooms, living rooms and master bedrooms. The top scoring designs in the aesthetics category had simple external geometry, reoccurring identical objects on the building façades, uniform colours, perfect equilibrium, conventional building grids, plain masses, and the least number of turns on the façade. In terms of energy performance, the home designs having the simplest building geometry and excluding any large protrusions, with simple roof designs and window to wall ratios of between 0.06 and 0.10 were among the top performing buildings. Lastly, as cost was directly related to area, the highest scoring building in the cost category were the homes with the smallest livable area. Using the above weighting factors, the top three designs out of the initial 22 homes were selected to carry forward into the next phase of the project.

Phase 2 demonstrated that using spray polyurethane insulation as well as rigid insulation, it is possible to meet the insulating requirements set by the Quebec Construction Code as well as satisfy the thermal bridging requirements. The top three designs were then narrowed down to one, primarily based on the renewable energy potential, as all three designs performed relatively equal in energy consumption per square footage.

Lastly, phase 3 of the project, concluded that by improving the exterior wall insulation as well as reducing the electrical loads, creates a positive effect towards reducing energy consumption. Additionally, the HVAC system plays a large role in energy consumption. Improving the system from a gas furnace to air-source heat pump showed large improvements that can be additionally improved by the implementation of renewable energy techniques such as the integration of photo-voltaic panels and geothermal energy, as well as a combination of them both.

Establishing an integrated design process is beneficial to designers and professionals, as well as the clients of the projects, in this case the homeowner. Incorporating and considering many aspects of a project and how they interact with each other from the beginning, not only eliminate conflicts, but also defines a common goal and establishes solutions to achieve the desired results.

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