ECONOMIC OPTIMIZATION OF THE BUILDING ENVELOPE FOR A HIGH PERFORMANCE MULTI-FAMILY RESIDENTIAL BUILDING

Byron Enns, M.Eng., Fitsum Tariku, PhD

ABSTRACT

The energy performance of buildings is an important issue for builders, and quantitative data is needed to help builders choose levels of insulation for various envelope components. Analysis is complicated by the fact that the optimal amount of insulation varies by goals, climate, architecture, construction methods, insulation material costs, and energy costs. This study analyzes many possible configurations of a case study building to uncover economically optimal envelope options. The case study building is a high-performance, three-storey, forty-five suite multi-family residential building that is now being built in the interior of British Columbia. Effective R-values were calculated for 5 wall options, 4 roof options, and 4 parkade ceiling options using established methodologies, which created 80 different envelope configurations. Then, the annual energy use of all the configurations were simulated using DesignBuilder, and cost information for each option was collected. Finally, the extra installation costs were compared to the present value of the predicted energy savings for a 30-year period. The results of the analysis indicate which specific configurations of wall, roof and parkade ceiling insulation are the lowest cost options to achieve different levels of energy savings. Finally, the study was replicated in Excel using the bin method, which produced similar optimal configurations. The absolute values of the energy savings from the bin method were not shown to be reliable, which was likely due to the number of simplifications used for the Excel calculation.

INTRODUCTION

Designers and builders in British Columbia and around the world are focusing more on the energy use of their buildings. This is seen in goals such as net-zero energy, LEED® certification, and Passive House certification. It is also seen in the building codes where some jurisdictions have plans to encourage high performance building envelopes and low energy buildings (Pape-Salmon et al. 2011)

In addition to thermal performance, economics plays an important role in the choosing the levels of insulation for a better-than-code building, because the installation budget can be spent on better windows, thicker wall insulation, thicker roof insulation, thicker slab insulation, different types of insulation, more efficient mechanical systems, addressing thermal bridges, or other items. A significant amount of research has been completed on this topic around the world with a concentration of studies in Europe. Researchers have examined economically optimal configurations of houses, both unrestricted and with additional requirements such as minimum insulation levels or net-zero energy use. However, as the price of electricity,

natural gas, materials and labor vary widely by region, much of this European research is not directly applicable to the construction industry in BC.

The purpose of the project on which this paper is based was to use building energy modelling to help a builder from Whistler, BC, make economically optimal design decisions for the envelope of their three-storey, forty-five suite multi-family residential building that will be built in Pemberton, BC. The builder's intention is to build a highly energy efficient building, and their interest is in allocating their resources in an optimal manner, instead of finding the economically optimal level of insulation.

Main Research Approach

The effective thermal resistance values and costs of different wall, roof, and parkade ceiling options of interest to the builder were calculated, and that information was used in conjunction with whole-building energy modeling software to determine the cost-optimal building configuration. In addition, the analysis indicates which other configurations could potentially be the optimal configurations under different energy cost inflation assumptions. The economically optimal configuration plus the potentially optimal configurations create the set of options from which the builder should select.

Replication of Research Findings Using Excel

In the final step of this study the analysis was replicated in Excel. The main advantage of Excel is computational speed. For this report, simulating all 80 options with DesignBuilder took approximately 18 hours on a desktop computer (with a W3670 Intel Xeon processor for reference). In contrast, the analysis for the same 80 configurations finished almost instantaneously in Excel. The number of possible options for the DesignBuilder section was limited due to computational time considerations. For example, if you added 4 window options and 1 more wall, roof and parkade ceiling option, the total number of simulations would increase to 600, which would take 135 hours to fully simulate on the same computer.

On the other hand, a simple Excel bin analysis has limitations because many factors were disregarded including solar gain, wind, the effects of thermal mass, and the internal gains schedule. At the end of this paper, the results of the Excel analysis are compared against the results for the whole-building energy analysis to review the accuracy of the Excel results, including both the ability of Excel to identify the same optimal & potentially optimal configurations, and the ability to correctly calculate the magnitude of the energy savings from increasing levels of insulation.

Overall Description of Test-Case Building

The test-case building is a three-storey multi-residential building with 15 suites per floor. The building will be rectangular and oriented north-south, with large east and west exposures. The builder plans on using an envelope-first approach to energy efficiency by focusing on minimizing envelope and infiltration heat loss.

Figure 1: A rendering of the case study building

Envelope Description of Test-Case Building

The builder chose their construction method for the test-case building, internal spray foam over structural wood frame, mainly because from their experience, that method can create a strong air barrier relatively easily. The minimum wall that they are considering consists of a 2x6 wood wall to the outside which will be the structural wall. The cavities of this wall will be filled with R-24 (RSI 4.2) fiberglass batt. The studs will be at 16 inch (406mm) on center due to structural requirements as calculated by the builder. A 2.5 inch metal stud wall will be installed to the inside using sufficient studs to meet the requirements of the drywall. There will be a 1 inch gap between the wood wall stud and the steel stud wall. The continuous 1 inch layer of spray foam between the two walls reduces thermal bridging and reduces the number of foam-to-material interfaces where leaks in the air barrier can develop over time.

The floors will be built using a Hambro truss system, which consists of steel trusses and poured concrete. The floors will rest on the top plates of the wood walls with 3.5 inches (89mm) of bearing, which allows 2 inches (51mm) of insulation to be placed outboard of the concrete floor slabs. The bottom plates of the next floor's wall will rest on the concrete with the same 3.5 inch (89mm) overlap.

The truss space between the parkade and the first floor will be filled with insulation. The walls of the parkade will be built with Insulated Concrete Forms, and the parkade floor will not be insulated.

The windows will be installed into the wood wall from the inside. 2 inches (51mm) of XPS and a flat 2x4 will be installed over all of the flanges. The inside face of the 2x4 will therefore sit in-line with the inside of the steel wall, and will provide a surface onto which the drywall can be installed around the window. This method was chosen by the builder to reduce thermal bridging around the window. They plan on using thermally broken triple pane windows as a minimum for this building.

In all cases, the builder chose the upper and lower amounts of insulation under consideration for each element.

Mechanical Description of Test-Case Building

A 100% outdoor air system will be used for ventilation. An HRV installed on the roof to recover heat from the exhaust air. Electric baseboard heaters will provide any supplemental heating needed. A DX-coil in the air supply air duct will supply cooling, but the airflow will be set for ventilation only, so cooling will be limited.

LITERATURE REVIEW

Whole building energy modelling tools allow many different configurations of a building to be evaluated for specific locations, designs and climates (Southern Califronia Edison 2000). There are two main approaches to whole-building optimization that are seen in previous papers.

One popular method is to use a building simulation tool, such as TRYNSYS or EnergyPlus (Attia et al. 2011), in combination with an optimization program, such as GenOpt (Ferrara et al. 2014). The optimization protocol evaluates the objective function of the configurations and choses which option to run next based the results obtained from the previous simulations. The optimal configuration is gradually narrowed down from the total set. The advantage of this method is that not every configuration needs to be simulated to arrive at the optimal solution, which saves time and computing resources (Attia et al. 2013). This method is often used when the goal is to minimize total lifetime costs, either for standard buildings or buildings with further constraints such as net-zero energy use (Lu et al. 2015). A second method is parametric simulations where a set of options are defined for each variable, and every combination within that set is simulated (Kurnitski et al. 2011).

Factors used in the optimization analysis can alter the results. Increasing the time frame and including the indirect cost of CO2 production will both result in higher optimal thicknesses of insulation (Barrau et al. 2014). Including uncertainties and defects in the insulation will also result in a higher optimal thickness of insulation(Aissani et al. 2014). Accounting for lost floor space loss will lower the optimal insulation thickness (Aissani et al. 2014). For this paper, the timeframe chosen was 30 years. CO2 costs are partially accounted for by the BC carbon tax included in the energy costs, but not otherwise. Insulation defects were assumed not to exist, and any floor space loss was not included as a financial cost because there are no restrictions to building outwards for the case study building. Finally, the embodied energy of the different insulation materials was not considered (Pierquet et al. 1998).

For the Excel replication portion of this paper there are several approaches described in literature. One method using degree days to determine the economically optimal amount of insulation is described by R.K. Beach (Beach 1965). This calculation uses a linear cost of insulation plot combined with a non-linear fuel cost plot, both with respect to the thickness of the insulation. The optimal point is then the point at which the combined cost is lowest. This method uses degree days to calculate the energy savings. Degree days are set from a base temperature, such as 18°C. The reason that it is not referenced to the indoor temperature is that at some point the internal gains will balance the heat loss, and therefore the hours with temperatures above the base can be ignored (Bailes 2014). In the case of this optimization, the temperature at which the heating loads will be met by internal gains will change based on the quality of the envelope. Therefore, to use the degree day method, the heating degree day base temperature would need to be determined on a

configuration by configuration basis.

An alternative to the degree day method is the bin method. With the bin method, climate data is used to create 'bins' of temperature. For example, the bins could be in 1 degree increments, and each bin would include all the hours per year in which the outdoor temperature sits within those bins. In the "modified bin method" described by Cane (Cane 1979), the internal/solar gains are calculated separately from the envelope and infiltrations loses, which allows the elimination of any bin that doesn't require heating energy. Because the energy balance is calculated for each bin of outdoor temperature, a method to include a second temperature profile for the parkade was not found. To account for the parkade, a parkade temperature was defined for each bin based on average temperatures throughout the year.

Methods to accomplish similar objectives have been developed by others (Cane 1979) that use correction factors to help account for the effects of solar gain, but for the purposes of this paper, a simple energy balance based on temperatures only will be used.

METHODOLOGY

The research objectives were achieved using different thermal modelling software packages, costing information, and financial analysis. In the first step, the different envelope and interface details were modeled and evaluated in THERM. Next, a whole-building energy model was constructed with DesignBuilder software. This model was used to quantify the energy savings from each of the different configurations. Next, cost information from the builder allowed the different details to be evaluated in terms of cost versus performance. Finally, an attempt to replicate the results using Excel instead of DesignBuilder was made.

Optimization protocols can be used to arrive at the optimal configuration without simulating every configuration. The desired "optimal configuration" is defined mathematically by the operator. An example would be the configuration with the lowest total combined construction plus 20-year energy costs. These protocols work by running a set of simulations, and using the results to intelligently select the next set. By simulating only those configurations selected by the algorithm, the computational time can be reduced dramatically. There are many different optimization protocols, and some have been shown to reliably arrive at the true optimal configuration.

Parametric analysis was chosen for this analysis instead, because in this case there is no specific objective function that is being optimized. Every combination of options will be simulated. The limitation of the parametric method is that the number of possible solutions examined will be smaller because every single configuration needs to be simulated, which requires significant computational resources. The choice of this strategy is supported by the fact that many of this building's design decisions were made outside of the scope of the research project. If more factors were to be included in the analysis, such as architectural choices, then parametric analysis would likely become impractical due to the sheer number of simulations needed. In addition, performing all the simulations parametrically provides a rich dataset.

Equivalent R-Value Calculations

THERM is a 2D thermal modelling software that is competent at calculating the effects of structure and thermal bridges on the overall thermal performance. The details that were modelled with THERM include different wall constructions, insulation thicknesses, window-to-wall interfaces, wall-to-roof interfaces, wall-to-floor interfaces. The starting points for all the details were the builder's standard construction details. This includes a double 2x6 wood frame wall with internal spray foam insulation for the walls. Different levels of insulation were examined from there, with the lower and upper levels of insulation under consideration set by the builder. The equivalent thermal resistance values were calculated from the THERM results using established linear and point transmittance methodologies.

The selected options are found in Table 1. There are 5 wall options, 4 roof options, and 4 parkade ceiling options. This results in a total of 80 different possible building configurations (5*4*4).

Table 1: All wall, roof and parkade ceiling options included in the study

Wall options	2x6 stud wall & fiberglass batt, plus 2.5" steel stud wall & 3" of 3/4lb foam (open cell)
	2x8 stud wall & fiberglass batt, plus 2.5" steel stud wall & 3" of 3/4lb foam (open cell)
	2x8 stud wall & fiberglass batt, plus 2.5" steel stud wall & 4" of 3/4lb foam (open cell)
	2x6 stud wall & fiberglass batt, plus 2.5" steel stud wall & 3" of 2lb foam (closed cell)
	2x8 stud wall & fiberglass batt, plus 2.5" steel stud wall & 4" of 2lb foam (closed cell)
Roof options	12" of 1/2lb foam (open cell)
	16" of 1/2lb foam (open cell)
	20" of 1/2lb foam (open cell)
	24" of 1/2lb foam (open cell)
Parkade ceiling options	6" of 1/2lb foam (open cell)
	8" of 1/2lb foam (open cell)
	10" of 1/2lb foam (open cell)
	12" of 1/2lb foam (open cell)

DesignBuilder Simulations

In the second step, DesignBuilder was used to construct a whole building energy model. This model was built to represent the proposed building as accurately as possible. DesignBuilder is an EnergyPlus based simulation program which is known for its ability to model complex situations. It is suitable for this task due to its flexibility and its Optimization module, which is designed to help perform cost-benefit analysis. Both DesignBuilder (DesignBuilder Software 2006) and EnergyPlus (Energy Plus n.d.) have been validated using ASHRAE 140, which is a test procedure designed to provide standard tests in which different energy models can be compared to one another.

The whole building model was built to reflect known variables, such as building location, orientation, fenestration, and uses, as well as variables to be tested such as wall thermal resistance, roof thermal resistance and floor thermal resistance. The specifics were gathered from the builder prior to commencing

on the energy mode through drawings, construction specifications, and interviews.

Each of the 45 suites was assigned one zone. This means that the conditions in each of the suite's rooms will be treated as uniform by the energy model. This simplification was used to reduce model complexity. Assigning multiple rooms to one zone can cause the model to underestimating the energy use, and eliminating the internal walls reduces the thermal mass of the building (Georgescu et al. 2015). This simplification was assumed to have a minimal impact on the results. The hallways were assigned one zone each, and the entranceways were assigned a zone in the cases where a door separated the hallway and entrance area. All the vertical spaces including the two stairways and the elevator shaft were assigned their own zones. The parkade was assigned one zone.

The values for occupancy numbers, occupancy profile, hot water use, miscellaneous profile and lighting profile were obtained from the *2014 Building America House Simulation Protocols* document by NREL (Wilson et al. 2014). The maximum lighting power and parkade lighting power were estimated in conjunction with the builder. The miscellaneous loads were estimated by obtaining the yearly energy use for representative appliances and devices from sources such as Energy Star and BC Hydro. The Latent and sensible fractions were obtained from the *2014 Building America House simulation Protocols* (Wilson et al. 2014). The miscellaneous electronics category was estimated.

There are assumptions that needed to be made to use DesignBuilder for this building. These assumptions were made on the best judgement of the authors and are not based on previous work. The first is that the air-to-water heat pump module in DesignBuilder does an adequate job of representing the direct expansion solar heat pump that will be installed in the building. As the solar assisted heat pump uses solar energy as well as outdoor temperature to evaporate the refrigerant, it should have higher COPs and should be able to operate under a wider temperature range. This means that the simulation could over or under-predict the heat pump and backup boiler's energy use.

The next major assumption is in the modeling of the parkade. An assumption about the amount of energy delivered to the parkade by the cooling vehicles would have a low level of accuracy. The high level of insulation for the parkade walls in combination with the HRV ventilation means that this assumption is critical for accurately modeling the parkade. The builder has built similar style parkades in the past, and they have a high degree of confidence in the temperatures of the parkade in winter. Their experience was used to tune the loads in the parkade.

Finally, this building will be built in Pemberton, British Columbia. Unfortunately, DesignBuilder does not include hourly weather data for Pemberton. The two closest options are Vancouver and Kamloops. It is evident from climate data that the Pemberton climate is far more similar to the Kamloops climate (Farmzone 2016) than Vancouver's (Farmzone 2016), and therefore the Kamloops climate was used for the simulations.

Cost vs Performance Analysis

The final step combined the results of the THERM analysis and DesignBuilder simulations outlined above. The equivalent resistances of each option were used in the whole building model, and the results for each permutation were calculated individually.

The builder has cost information for each of the details and options. The material and installation cost data came from vendor quotes, so the information is likely to be accurate. This information was gathered through interviews with the builder and used in a cost benefit analysis.

The savings in energy use for each configuration were then compared to the extra expense for those configurations. The total 30-year energy savings were calculated with a 4% yearly energy cost inflation. The discount rate was set at 7%, which approximates an average rate of return on private sector investment (US Office of Management and Budget 1992).

Excel Comparison

A spreadsheet was set up to calculate the cost and energy use for each configuration, and those variables were compared against the values for the base case configuration.

A bin calculation was used to calculate the yearly energy use for each option. The bin calculation calculates the energy deficit for each bin by taking the internal gains and removing infiltration losses and the envelope losses. The energy deficit represents the energy requirement to be met by the mechanical systems, and these values were modified by the efficiency of the heating system. Any bins with a negative deficit do not require energy for heating and were disregarded.

The average miscellaneous energy use per hour was generated by dividing the total energy delivered to the building by 8760 hours per year, and multiplied by a factor of 0.8 to account for load disparity. In addition, the building uses a heat pump. To account for the efficiency of the heat pump, a mechanical efficiency factor of 1.5 was used. These factors were chosen based on judgement, and the accuracy of these factors is not high. This is an area that could be improved with future research and analysis.

ANALYSIS AND RESULTS

The results for both the DesignBuilder analysis and the Excel analysis were graphed to show the energy cost savings against the extra installation cost.

Result for DesignBuilder Configuration Analysis (Installation Cost Versus Energy Savings)

All the results presented below are referenced to the base case. This means that the extra insulation cost of the base case is zero, and the savings of the base case is zero. There are 80 unique configurations represented in Figure 2. The individual configurations can be identified with the legend. The wall options are represented by the connecting lines, the roof options are represented by the diamonds, and the parkade ceilings are represented by the dashes.

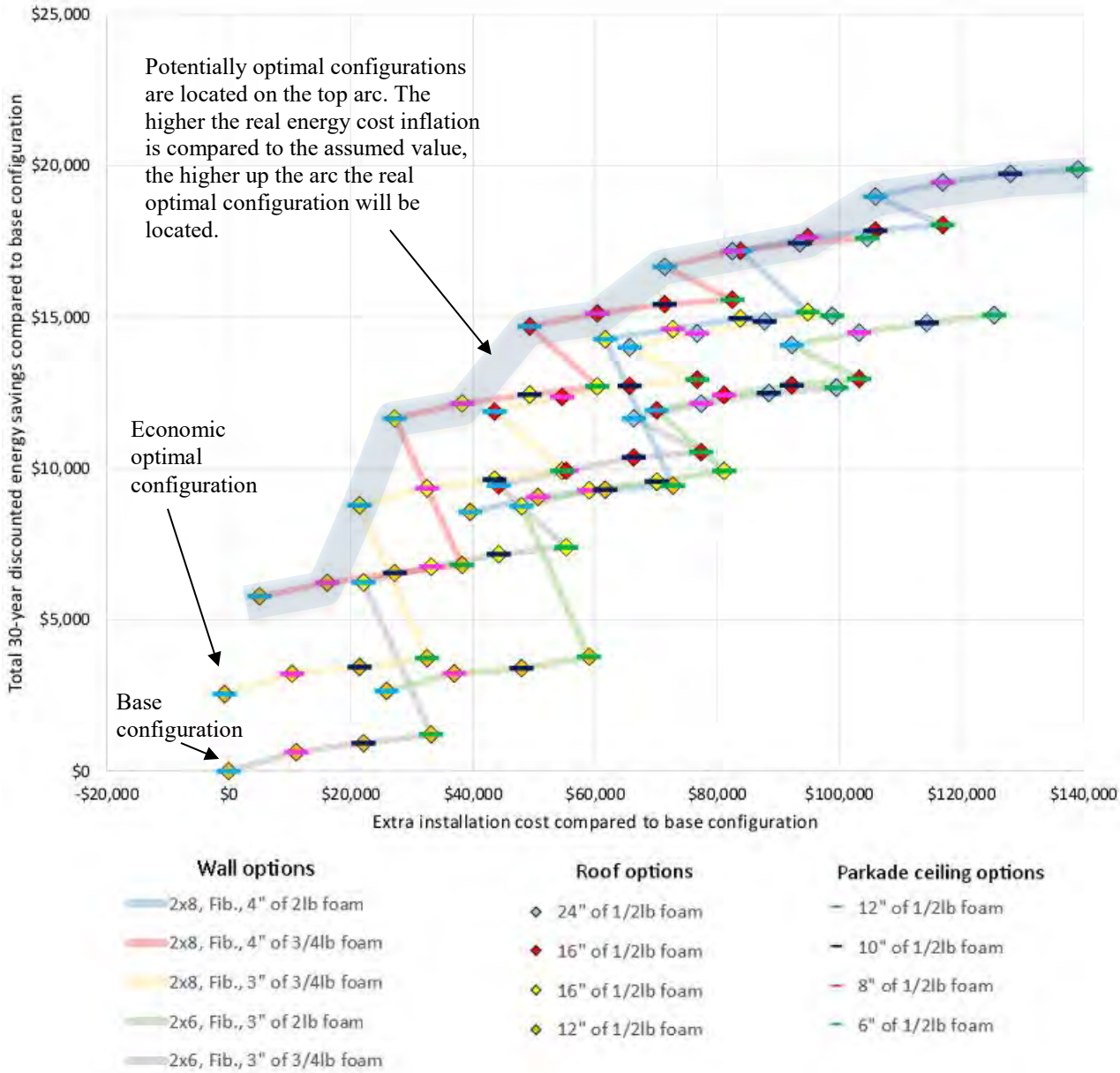

Figure 2: DesignBuilder results showing all possible combinations of wall, roof and parkade ceiling options

The x-axis of this graph increases in installation cost compared to the base case, and the y-axis increases in total 30-year energy cost savings compared to the base case. To use this graph, locate a chosen installation cost premium on the x-axis, and then the best configuration for that cost is the closest to the top on the vertical line above it. Looking at the graph, the performance difference between the best and worst configurations with the same cost is up to 50% of the difference between the base case and the best case studied. Another way to use the graph is to locate a given performance premium above the base case on the y-axis. The best configuration for that level of performance is the left-most configuration on that horizontal line. Looking at the graph, the installation cost difference between the best and worst configurations (that both deliver the exact same performance) is up to $70,000.

Result for Excel Configuration Analysis (Installation Cost vs. Energy Savings)

The results presented below represent the same 80 configurations as in the DesignBuilder case. Again, the extra cost and savings are referenced to the base case.

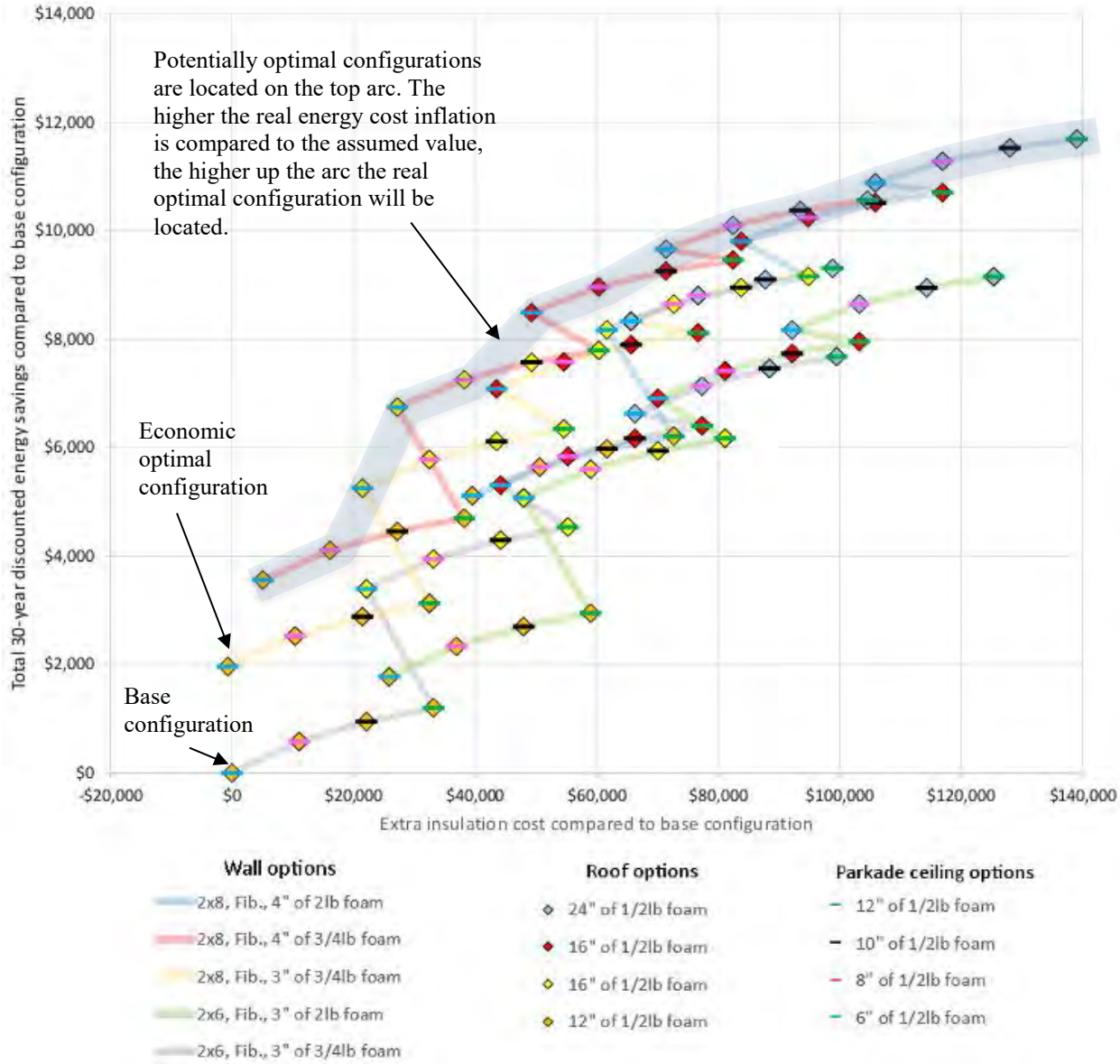

Figure 3: Bin method results showing all possible combinations of wall, roof and parkade ceiling options

The general shapes of the graphs produced by the two methods are similar, although there are some differences. The magnitude of the savings does not match well, which is expected because of the number of simplifications and assumptions used in the Excel analysis.

DISCUSSION AND RESEARCH FINDINGS

Configuration Recommendations

The optimal configuration is found by comparing the extra installation costs to the energy cost savings in Figure 2. The economic optimal case is labeled as "Economic optimal configuration" on the graph, which is the configuration with the lower life cycle cost. This configuration is not of interest to their builder, as the intent is to build a building with a higher level of performance than would be delivered at the economically optimal point. It is important to note that the base levels of wall, roof, and parkade ceiling insulation levels were determined by the builder. Because of this, it is possible that the true economic optimal configuration has a lower level of insulation than is shown by this analysis.

The remaining configurations along the top arc of the graph show other potentially optimal configurations. These configurations could become the economically optimal configuration if the real inflation of energy cost is different than assumed. The higher the future energy costs rise above those assumed is this analysis, the higher up the arc the true optimal configuration will be. Note that some of the configurations on the arc will be skipped as energy cost assumptions increase.

The builder should select any of the configurations indicated in Figure 2 labeled as "Economic Optimal" or "Potential Optimal". The farther up the outside arc, the higher performing the configuration, but the higher the cost premium. Cost premiums can be calculated using the information on both axes. Any of the configurations that were not indicated as the optimal or as a potential optimal should not be selected. In all cases, if the configuration is not in the optimal/potentially optimal set, there is another configuration that delivers the same level of performance for a lower installation cost.

Some points can be seen from the graph. First, there is one configuration which is performs better than the base case but costs less. This was found to be from the cost premium on R-24 fiberglass insulation for 2x6 studs compared to the standard batts used in the 2x8 walls. Another configuration delivers 25% of the total energy cost savings for a very small cost premium. A different configuration delivers over half of the energy cost savings of the most insulated configuration for only 20% of the installation cost premium.

Another immediate observation is that most of the optimal configurations use the second-best wall (represented by the pink line in Figures 2 and 3), so an upgrade to that wall is a clear decision. Also, all the optimal cases use walls that are thicker than the base case wall. Extra costs involved with thicker walls have not been accounted for in this analysis. For the case study building, the extra wall thickness can be added to the exterior, and does not reduce the square footage of the building. If the loss of internal square footage is a significant issue, then the two standard thickness wall options should be examined for the optimal configuration.

In addition, the optimal configurations show a low to medium level of insulation between the parkade and the first floor. As indicated earlier, an assumption was made for the parkade temperature based on the experience of the builder. If the real-life temperatures are lower than the predicted temperatures, the thermal resistance of the parkade ceiling will have a greater impact than is indicated by this analysis. Conversely, if heaters are used to keep the parkade at higher temperatures, then the benefit from the parkade ceiling insulation will be smaller than predicted.

Another factor that is important in the energy savings results is the efficiency of the mechanical system. The more efficient the system is, the lower the energy savings will be for a given increase in the envelope's

thermal resistance. This is important because the analysis in DesignBuilder was performed with an air-to-water heat pump, whereas the real building will use a solar assisted air-to-water heat pump. If the solar assisted heat pump is significantly more efficient than the one used in the model, then the energy cost savings in this analysis will be over-predicted.

Replication of Research Findings Using Excel

The bin method identified the same optimal configurations as the DesignBuilder simulations.

The magnitudes of the savings do not match however. The most likely reason for this is that many factors were disregarded in the bin method calculation, including solar gain, thermal mass, wind, and internal gain schedules. Previous research has indicated that the degree-day method will over-predict energy use because thermal mass is ignored (Fumo et al. 2010).

The miscellaneous energy was averaged throughout the entire year, and modified by a factor to account for load disparity. Increasing the average miscellaneous energy decreased the energy savings, and decreasing the average miscellaneous energy increased the energy savings. In addition, in this example the bin method results were found to be sensitive to the temperature profile of the parkade. Minor modifications to the parkade temperature result in large changes to the results chart.

Finally, the simulation relies on assumptions for the efficiency of the mechanical systems, which would have a large effect of the potential energy savings. In this case, increasing the average assumed efficiency lowered the savings, and decreasing the average assumed efficiency increased the savings. This building is not fully air-conditioned, so the assumptions regarding solar heat gain would not have affected the results as much as they would have if it was fully air conditioned.

While this method seems reliable for predicting the relative ranking of the configurations, it is the author's opinion that this method requires more development and validation before it is used to predict the magnitude of energy savings.

CONCLUSION

Configurations of the test-case building were analyzed considering local factors including the cost environment by comparing 80 configurations with different combinations of wall R-values, roof R-values, and parkade ceiling R-values. It is clear from the results that the walls are the most effective place to spend money above the base configuration, followed by the roof, and with the parkade ceiling in last place. None of the optimal wall configurations use 2x6 framing, so upgrading to 2x8 framing is a clear choice because the wall thickness is not critical with this building. The result graphs give the builder the information required to examine tradeoffs and select the best configuration for their desired level of performance.

In this analysis, even the base case wall, roof, and parkade ceiling options represent an excellent level of performance. This is seen in the low energy savings numbers for the better options, where the energy cost difference between the best and worst configurations amounts to just over $1000 per year. This savings will increase if additional carbon costs are added to the energy price in the future, or if energy prices rise

higher than the assumed 4% per year. The energy savings would have been more dramatic if the code minimum wall, roof, and parkade ceiling options were included in the analysis.

In addition, this study shows the benefit of using building energy simulation programs to optimize envelope choices. The analysis revealed that there are configurations that have a $70,000 premium for installation cost but deliver the same level of performance (Figure 2), and this information is helpful to the builder. In many projects, the energy modelling is completed for code compliance or certification credits. In these cases, the additional work required to complete a configuration analysis is relatively low. Additionally, published thermal bridging values are available for common construction methods, which would save a significant amount of time for the analysis.

Finally, the comparison between the DesignBuilder results and the Excel results indicates that the bin method can be used as a tool to help builders chose levels of insulation in different envelope components. The magnitude of the savings potentially has a significant degree of error. Further research is required to determine if the accuracy of the magnitudes can be verified and improved.

A scenario where the bin method analysis would be very useful is when a builder intends on building a better-than-code envelope, and wants to know where a fixed amount of extra money would best be spent. If the builder has a fixed budget for upgrades, then the relative ranking of the configurations is important, but the magnitude of the energy savings is not. Because Excel was shown to identify the relative ranking of the options with accuracy, then the results can be obtained in Excel with much less time and effort than with a whole building energy simulation program. If, on the other hand, the accuracy of the energy savings is important, such as a situation where a builder wants to know if money should either be spent on the envelope or on the mechanical system, then whole building energy modelling would produce better results.

The Excel method could also work well in tandem with whole-building energy simulation. Two simulations could be used to calibrate the Excel calculation, and then the Excel sheet could be used to rapidly compare different scenarios.

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